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August 1996

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Station

Environmental Impact Research Program

A Review of Sensors Appropriate for Assessment of Submerged Coastal Habitats and Biological Resources

by Donald C. Rhoads, Jo Ann Muramoto, Roger Ward
Science Applications International Corporation

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Prepared for Headquarters, U.S. Army Corps of Engineers

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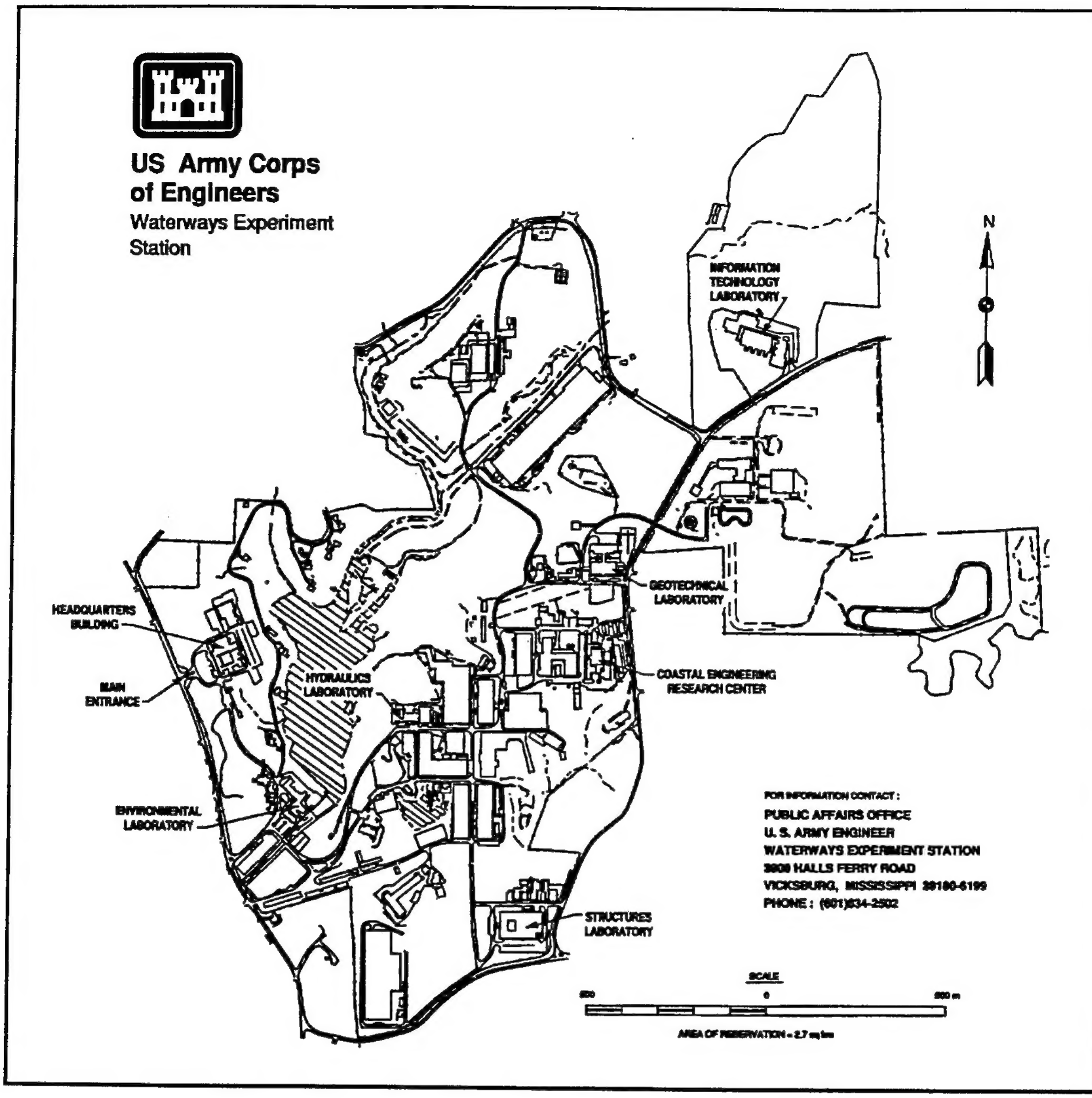

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Preface

The work reported herein was conducted by the U.S. Army Engineer Waterways Experiment Station (WES) for Headquarters, U.S. Army Corps of Engineers (HQUSACE). Funding was provided by HQUSACE through the Environmental Impact Research Program (EIRP), Work Unit 32883, entitled "New Technologies for Evaluation of Aquatic Habitats." Program Manager for the EIRP was Dr. Russell F. Theriot.

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1 Introduction

This review has been prepared for the Coastal Ecology Branch, Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station. During the planning, coordination, and construction process for dredging, dredged material disposal, shoreline protection structures, and other projects, the Corps of Engineers (COE) is mandated to assess environmental impacts and to seek acceptable alternatives. These activities have historically been limited by logistical difficulties in conducting surveys of coastal habitats and biological resources. Conventional techniques are often expensive, non-quantitative, or logistically impractical for broad area surveys. This review identifies state-of-the-art technologies that are candidates for efficient mapping and monitoring of subtidal soft-bottom substrates, hard grounds, and fisheries resources.

Remote sensing has traditionally been thought of as airborne or satellite imaging. However, remote sensing is being rapidly expanded to include in-water and in-sediment sensors. Several defense conversion initiatives are underway to modify military surveillance technologies for environmental mapping and monitoring. It is the purpose of this review to make an inventory of appropriate technologies and to identify the data sources. Each technology is succinctly described with respect to (a) sensor description, (b) data outputs, (c) examples of sensor/system outputs and evaluation relative to the Corps' mapping and analysis needs, (d) costs to acquire, operate, and maintain, (e) technology maturity and risks, (f) future development requirements, and (g) information sources and technical contacts.

Sources of Information

Several workshops and international meetings on remote sensing as applied to the environment have been held in the recent past. Proceedings from these events are important sources for identifying new breakthroughs and provide a summary of existing capabilities and future prospects. Klemas, Thomas, and Zaitzeff (1987) reported on proceedings of an important early workshop on estuarine remote sensing. In 1992 and 1993, the Marine Spill Response Corporation, the U.S. Environmental Protection Agency (EPA), and the Environmental Research Institute of Michigan held the first and second Conference on

Remote Sensing for Marine and Coastal Environments in New Orleans (Environmental Research Institute of Michigan 1992 and 1993). The two resulting four-volume summaries provide information on the state-of-the-art sensor technology for coastal remote sensing. In 1994, two conferences on remote sensing were held: (a) the National Oceanographic and Atmospheric Administration (NOAA) sponsored Remote Sensing of Coral Reefs Conference at the New England Aquarium, Boston, May 17-19, and (b) the International Symposium on Spectral Sensing Research 1994 (ISSSR 1994) in San Diego, July 10-15. Proceedings of these two meetings have not been published to date, but Science Applications International Corporation (SAIC) participated in both, and the relevant technologies are included in this report. Online literature searches using Internet and search categories for environmental sensors were also employed. A major fraction of the peer-reviewed literature came from the collected reprints of one of the authors (D.C. Rhoads).

Sensor Categories

Sensors and techniques reviewed in this report are limited to those that specifically address assessment of submerged coastal habitats (Table 1). Features of interest such as bottom type, distribution of plants, epifauna, infauna, and demersal fish require that the sensors be capable of operating in or "looking through" water, and acquired information must have sufficient spatial resolution to map the above features of interest. These constraints eliminate many traditional remote sensing technologies such as satellite or high-flying aircraft platforms as spatial resolution is too low or the signal is compromised by water cover. This review therefore focuses on high-resolution in-water sensors or low-altitude airborne sensors that have the capability of some water penetration. Well-established and well-known techniques such as conventional underwater photography and video imaging are deliberately excluded. For optical systems, categorization of sensor types (active or passive) is dictated by the electromagnetic spectrum (Figure 1). For acoustic systems, categorization is determined by the frequency range of the sensor and if the sensor is towed in the water or deployed on the seafloor (Figure 2).

Table 1
Categories of Reviewed Sensors

Deployment Platform	Name of System
On-Bottom	Sediment Profile Camera
	REMOTS® Hyperspectral UV Imaging Profile Camera
	Megahertz Acoustic Sled
	Acoustic Subseabed Interrogator (ASI)
In-Water	Laser Line Scan System
	Gamma Sled
	Continuous Sediment Sampling System (CS^3) Sled
	Acoustic Side-Scan
	RoxAnn
Airborne	Hyperspectral Imaging
	LIDAR

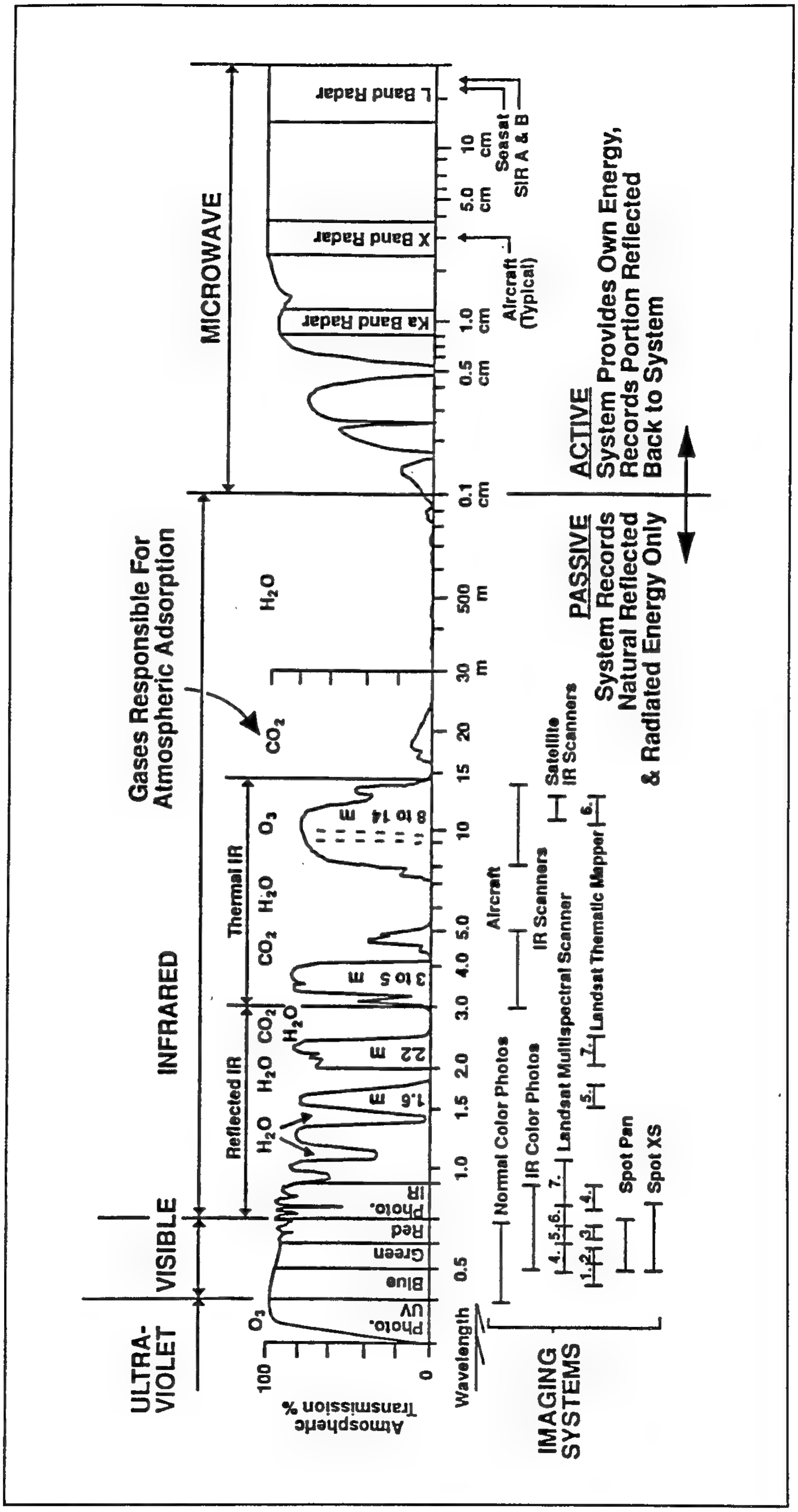


Figure 1. Expanded electromagnetic spectrum and optical remote sensing systems

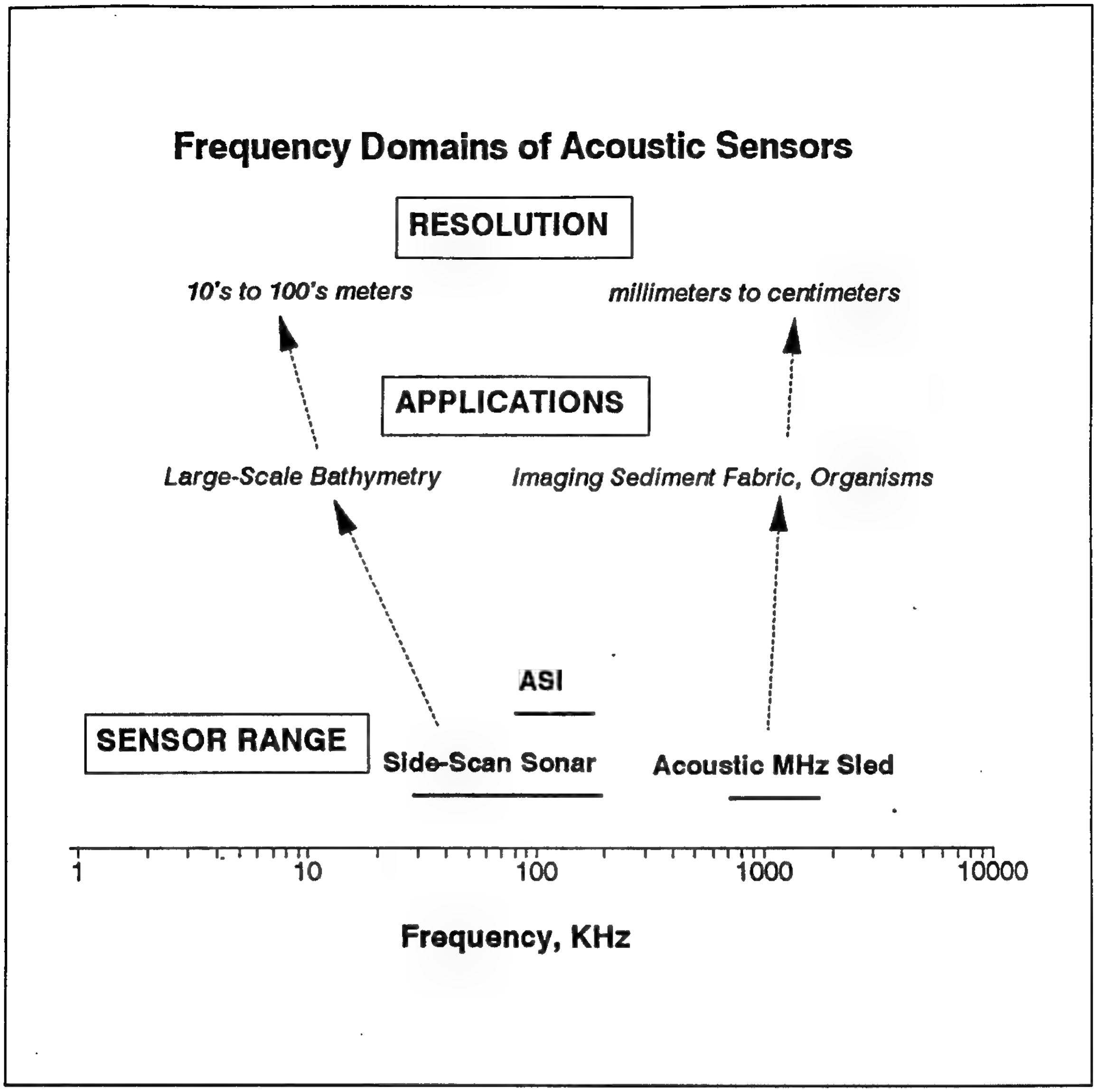


Figure 2. Frequency ranges for in-water acoustic sensors

2 On-Bottom Sensors

Sediment-Profile Imaging (SPI)

Sensor name: Sediment-profile camera

Sensor category

In-water/in situ imaging of soft-sediment bottom profiles.

Description

An underwater camera system is lowered to the seafloor from a vessel (Figure 3, 1). Once deployed on the bottom, the camera operational sequence is automatic. The optical prism penetrates the bottom at a slow rate of descent of about 6 cm/sec to avoid physical disturbance of the bottom to be imaged (Figure 3, 2). When the prism has fully penetrated the bottom, a photograph is taken of the sediment column in profile utilizing an internal strobe (Figure 3, 3). After the image has been taken, the film is automatically advanced, the strobe is rearmed, and a pinger signal (optional) is transmitted, indicating that the sequence is completed (ca. 15 sec). The camera is then pulled out of the bottom, and the vessel repositioned to acquire additional profile images.

Data outputs

The initial output from the sensor is a color transparency. The analog image is digitized and input into an image analysis system for measurement of linear distances (penetration depth, boundary roughness, depth to features of interest, thickness of dredged material layers, etc.). The mean thickness of the oxidized surface layer is measured by 256 grey-scale density slicing and dividing by the window width. Major modal grain size is estimated by comparing image grain with an imaged set of standards. Biological status is inferred from imaged biogenic structures.

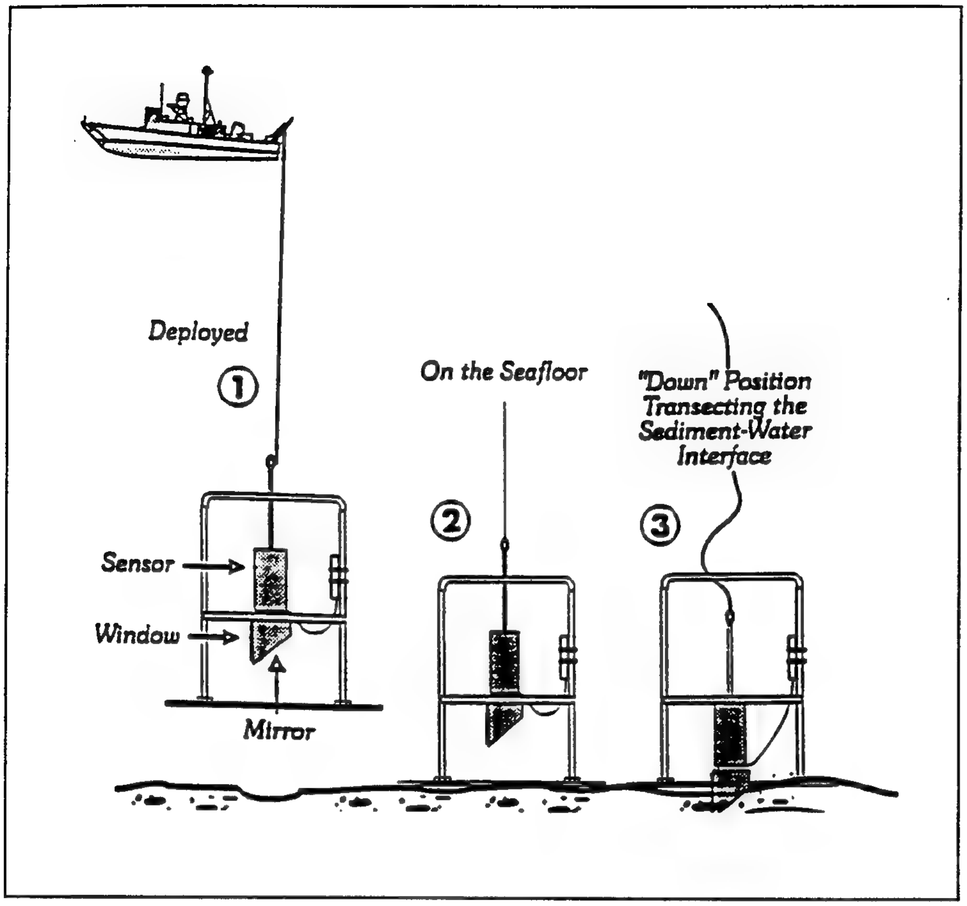


Figure 3. Deployment and operational sequence of a sediment-profile camera

Examples of sensor outputs

Figure 4 shows an example of data output with input to a geographic information system (GIS) for resource mapping. This system is appropriate for COE projects involving subtidal soft sediment characterization such as baseline surveys, predisposal site assessment, postdisposal compliance monitoring, defining dredged material footprints, long-term monitoring of dredged material, and documentation of faunal colonization. The high resolution afforded by sediment profile imaging is especially useful for mapping layers of dredged material that are too thin to be detected by precision acoustic methods (Figure 5).

Costs to acquire, operate, maintain

The system includes (a) the camera system, (b) field color slide development kit, and (c) laboratory computer image analysis system. Costs of

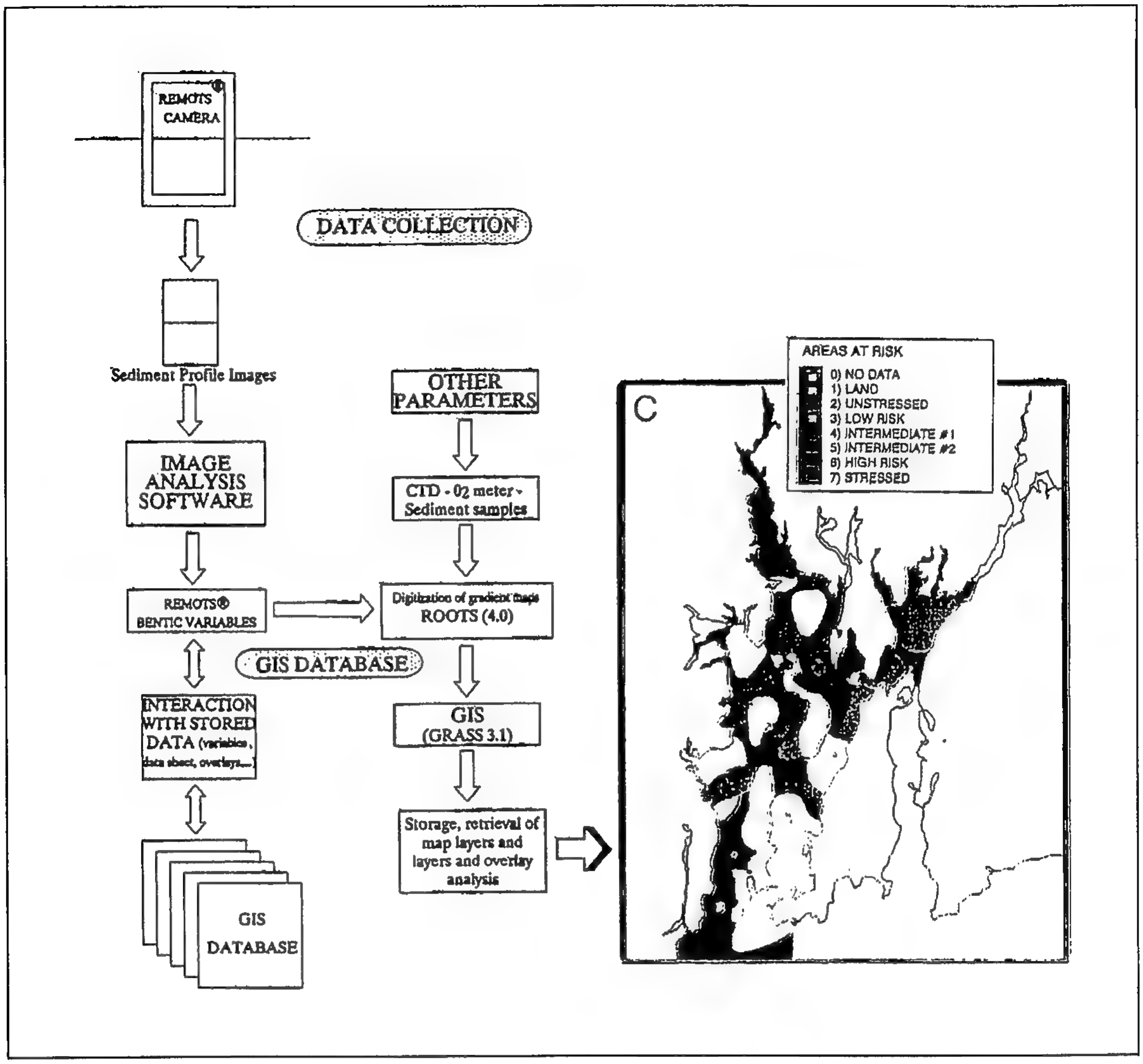


Figure 4. Example of sensor output linked to a GIS mapping system

(a) range from $25K to $50K depending on the vendor, (b) $0.6K, and (c) $12K, including both software and hardware. Maintenance is required for the sensor system at approximately $1K/year, and expendables for the overall system cost about $1K/year for intensive use.

Technological maturity and risks

Technological maturity level is high; the existing camera system has been used commercially around the world for over 20 years.

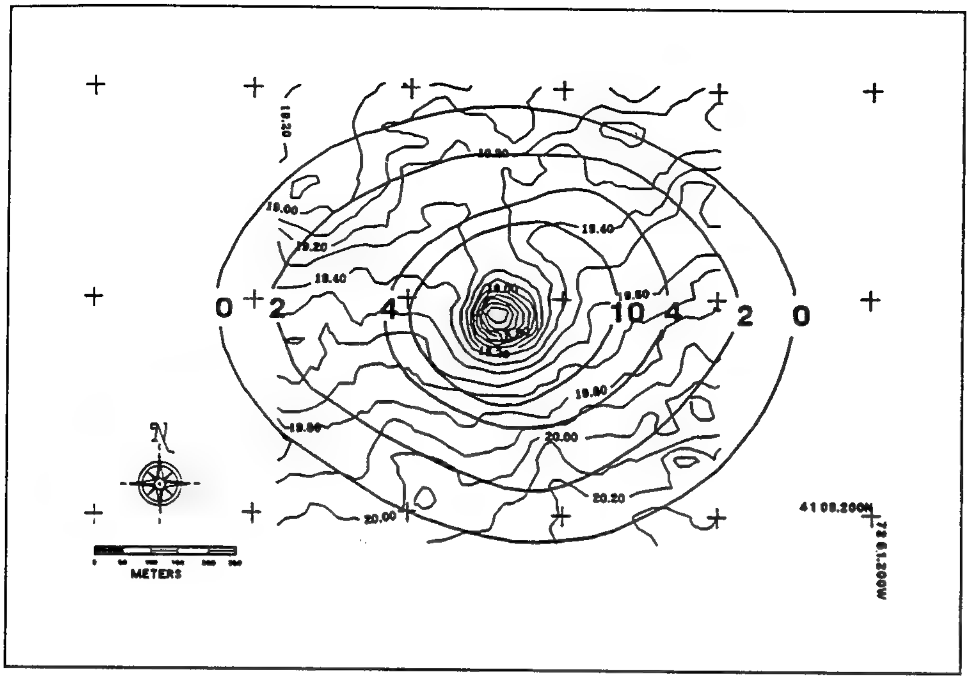


Figure 5. Example of sediment-profile camera footprint and thickness mapping of dredged material deposit (Note dredged material thickness contours in centimeters overlain on bathymetry)

Future development requirements

It is recommended that the existing photographic camera be replaced with a digital still frame camera so that data acquisition is initially in digital form. This design modification would eliminate the step of film development in the field, allow digital image filing and enhancement, and facilitate immediate "reading" of imaged features in the field. Digital cameras will add about $10K to the existing sensor price, but the benefits in increased speed of operation and analysis will justify the added cost. The technology risk for digital camera development and deployment is low to moderate. The underwater field performance of a still frame digital camera is unknown.

Information sources

Dr. Donald C. Rhoads is the inventor and has been a major user of this instrument over the past 20 years. The SAIC does not build the sensors but purchases them from outside vendors.

Dr. Robert Diaz, Virginia Institute of Marine Science, Gloucester Point, VA, has designed a shallow-water version of the sediment profile camera system and used it extensively in assessments at dredging and dredged material disposal projects.

Hyperspectral UV Imaging Spectrometer

Sensor name: Remote Monitoring of the Seafloor® (REMOTS) UV sediment-profile camera

Sensor category

In-water imaging of UV-excited emission of organic contaminants in soft-sediment profiles.

Description

The operational sequence for this spectrometer is similar to that described previously for the sediment-profile camera. However, the imaging ultraviolet (UV) spectrometer is capable of analyzing the fluorescence signatures of organic compounds contained within the imaged sediment profile. Once the optical prism penetrates the seafloor (Figure 6), the CCD digital camera is actuated from the onboard command center (Figure 7) to collect red, green, and blue (RGB) spectra of the sediment profile and assemble these three overlapping spectral bands into a digital color image. The RGB inbound bands are defined by the appropriate color filter located within a mechanical filter wheel in front of the camera lens (Figure 6, component 6). The RGB image is sent to display and storage (Figure 7, modules 1 and 2), and the onboard command station then is instructed to illuminate the same sediment profile with a narrow band of UV excitation light from a 1,000-W mercury vapor lamp (Figure 6, component 12). A mechanical filter wheel in front of the lamp defines the excitation band width (Figure 6, component 15). Up to four UV excitation bands can be sequentially programmed. A blocking filter in front of the CCD camera (Figure 6, component 7) excludes excitation light from entering the camera.

If there is fluoresence produced from organic compounds in the imaged sediment, the UV emission will be shifted to longer wavelengths (toward the red end of the electromagnetic spectrum as shown in Figure 1). The "red shift" emission light will enter the camera lens because it is of a longer wavelength than the upper band exclusion limit of the blocking filter. If no fluorescing compounds are present in the imaged sediment profile, the resulting image field will be black. If fluorescence is emitted, those parts of the image containing fluorescing compounds (humic acids, chlorophyll, polyaromatic hydrocarbons (PAHs), fuels, crudes, creosote, etc.) will be illuminated in false color. The sensor is capable of collecting emission spectra at 17, 10 nm-wide bands. The maximum number of excitation/emission signatures that can be obtained is 68; 4 excitation bands × 17 emission bands. Most applications will not require a full set of 68 data sets. The majority of contaminant problems will be resolved with 6 to 12 spectra. Bottom time for collecting up to 17 spectra is estimated to be less than 60 sec.

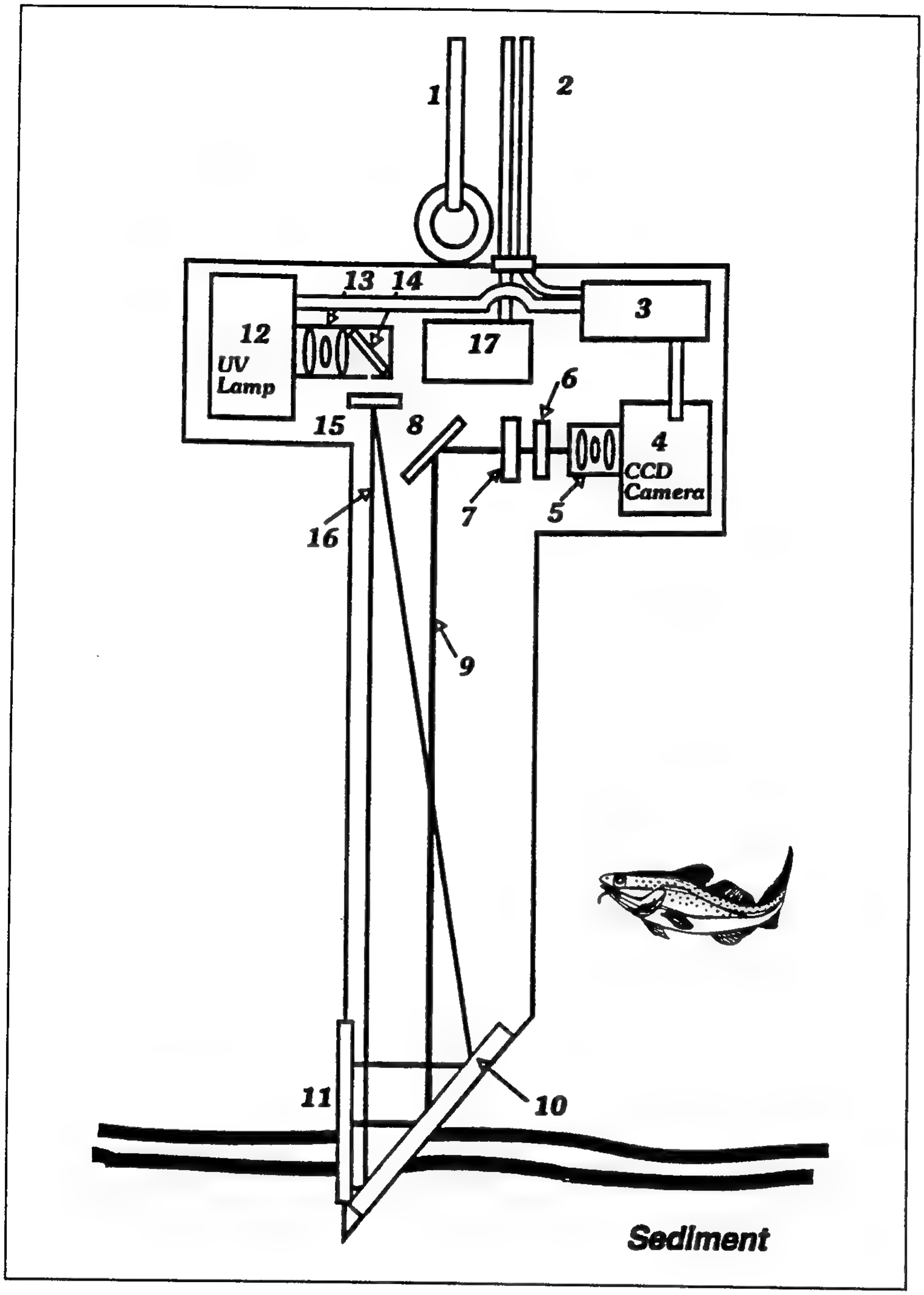


Figure 6. Schematic cross section of the optical sensor showing major components: (1) lowering cable, (2) power and signals cables, (3) controller for CCD camera and Hg lamp, (4) thermal electrically cooled CCD camera, (5) lenses, (6) spectral filter in filter wheel, (7) excitation blocking filter in filter wheel, (8) 45° UV coated mirror, (9) sediment profile image path, (10) 45° first surface UV coated mirror, (11) quartz pressure window, (12) Hg lamp, (13) collimating lenses, (14) UV coated mirror, (15) excitation filter in filter wheel, (16) excitation light path, and (17) power control/conditioner for light and camera (from Rhoads et al. 1994)

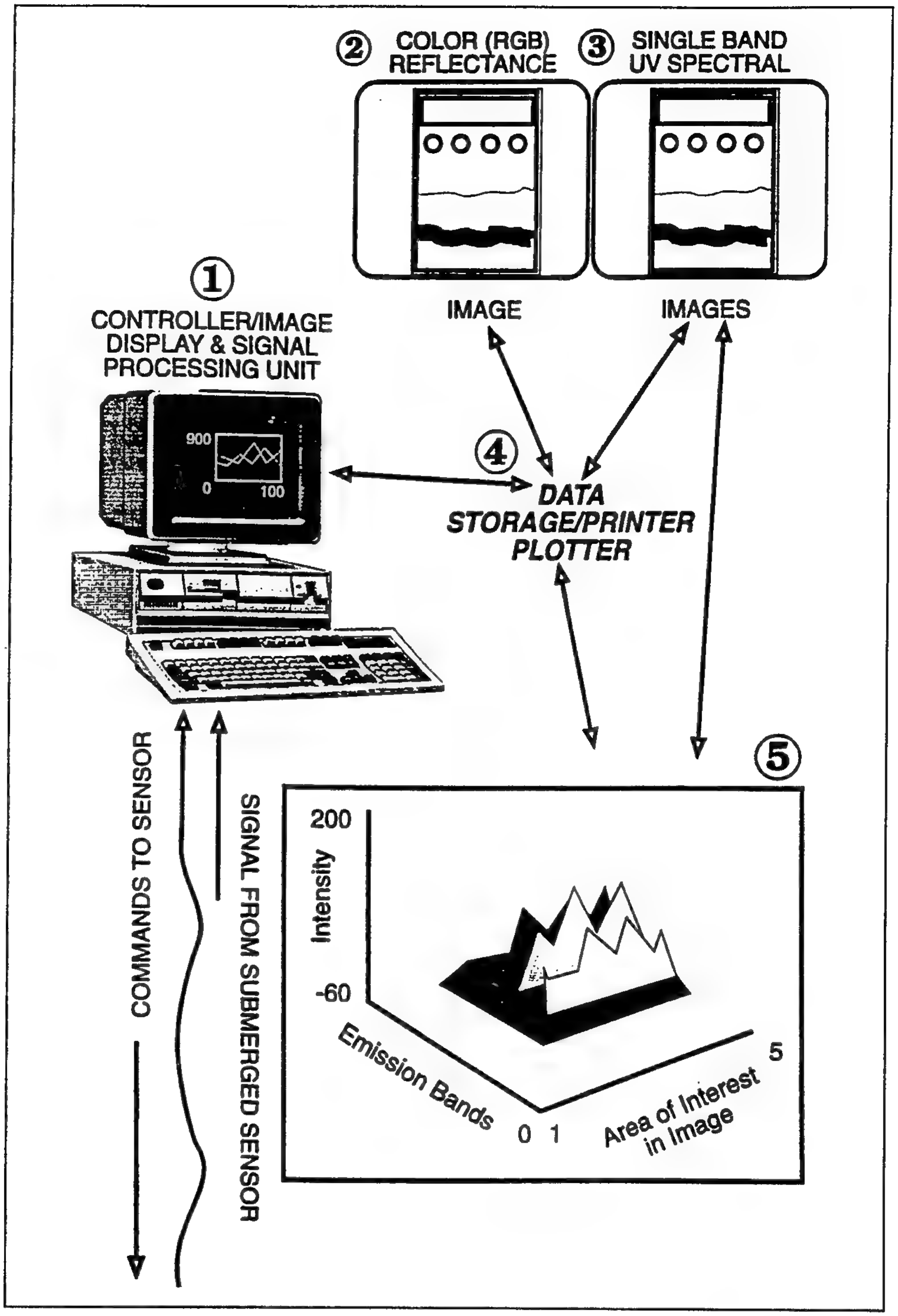


Figure 7. Shipboard onboard command center: Controller and image acquisition and processing unit (1). Commands are down-linked to sensor control functions and to coordinate measurement sequencing. RGB color images (2) and UV emission spectra (3) are uplinked to the deck computer where they are displayed, stored, printed (4), and spectrally analyzed (5) (from Rhoads et al. 1994)

A unique feature of this spectrometer is that it displays reference standards in the field of view at the top of the imaging window. These standards are used for blank correction, comparing imaged fluorescence with known standards, and evaluating overall precision and accuracy of the sensor. The threshold for detection of this instrument is ca. 100 ppm.

Data outputs

The initial output from the sensor consists of an RGB digital color image and up to 68 excitation/emission spectra of the same image. The RGB image can be input to an image analysis system for enhancement and measurement of linear distances (penetration depth, boundary roughness, depth to features of interest, thickness of dredged material layers, etc.). The mean thickness of the oxidized surface layer is measured by 256 grey-scale density slicing and dividing by the window width. Major modal grain size is estimated by comparing image grain to an imaged set of standards. Biological status is inferred from imaged biogenic structures.

Emission spectra are used to identify component compounds by referring to a specially prepared digital standard library developed from wet reference sediments spiked with known concentrations of a range of EPA priority organics. Pixel unmixing routines are used to identify individual compounds within complex mixtures. Emission intensity data are used to estimate concentrations of fluorescing compounds, and their spatial distributions can be overlain on the RGB image to relate concentrations to physical stratigraphy such as dredged material layers or biological features such as bioturbation depths, tubes, and burrows.

Examples of sensor output

Figure 8 shows an example of data output from a laboratory prototype spectrometer. In this case, the sediment column was spiked with a triple mixture of the PAHs, anthracene, benzo(a)pyrene, and pyrene.

This system is appropriate for COE projects involving identification of contaminant "hot spots" defined as $\geq$ 100-ppm contaminant hydrocarbons in subtidal soft sediment environments. This sensor is appropriate for surveys of potential dredging sites and other kinds of baseline surveys, postdisposal compliance monitoring, remediation monitoring, subtidal oil spill mapping and monitoring, defining dredged material footprints, long-term dredged material monitoring, and documentation of faunal colonization. Sediment profile imaging is especially useful for mapping layers of dredged material that are too thin to be detected by precision acoustic methods (Figure 5). This sensor can be used in all of the ways that the previously described profile camera is being used but includes the ability to image, identify, and quantify organic contaminants.

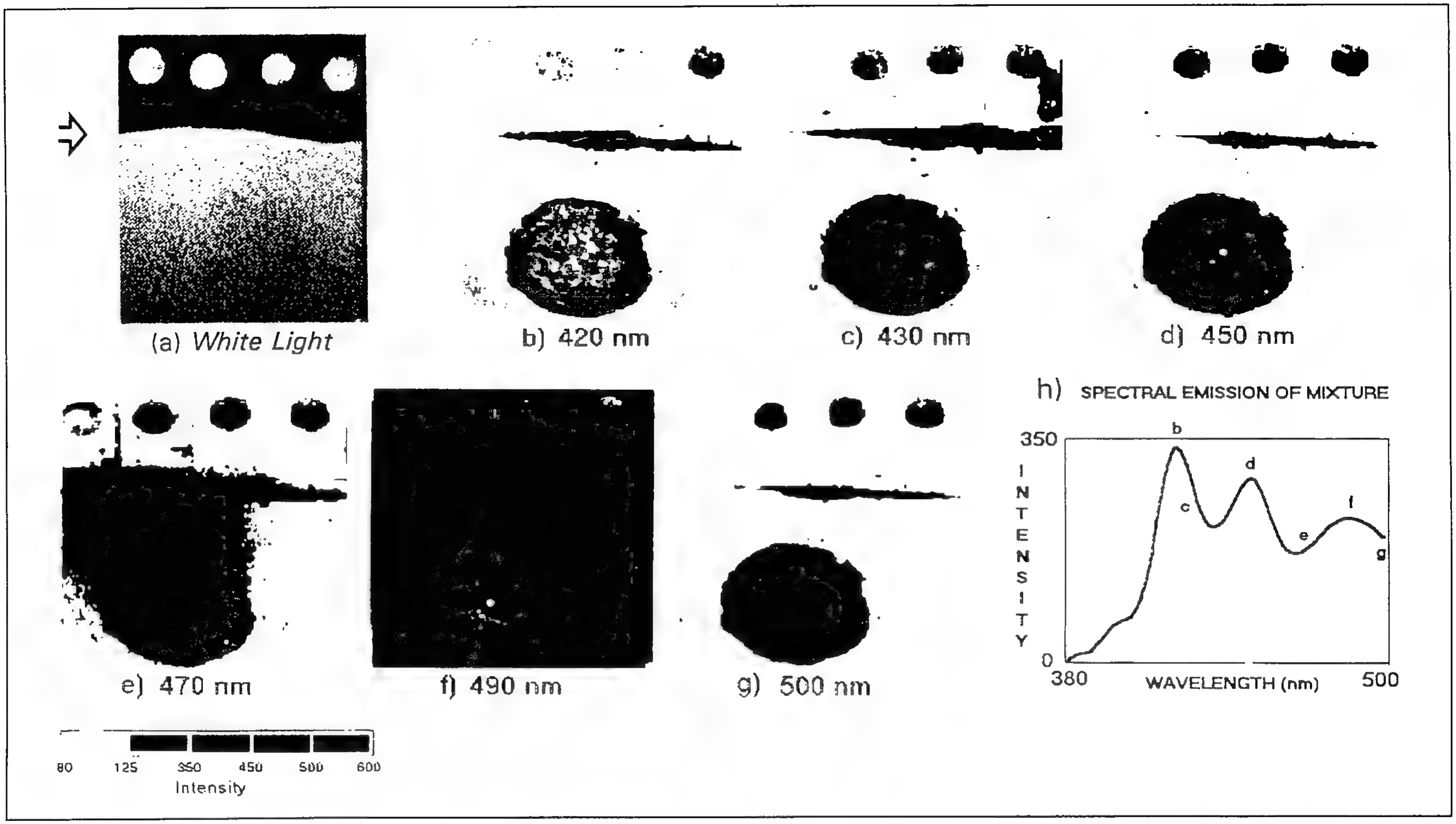


Figure 8. Example of spectral imaging and analysis from a laboratory prototype spectrometer: (a) "white light" reflectance image of the sediment column to be spectrally analyzed, including four reference cells (top of imaging window). Note that large circular patch containing spiked mixture of 500 ppm each of anthracene, benzo(a)pyrene, and pyrene, is not visible in reflectance but is visible in UV emission (images b-g). Arrow marks sediment-water interface. UV-excited emission intensities (b-g) are obtained from same image field using a 314-nm excitation band and emission bands at 420, 430, 450, 470, 490, and 500 nm. Reference cells contain sediments spiked with 1,000 ppm of individual PAHs and a blank (clean sediment). Spectral intensities are corrected for background by subtraction of blank. (h) Emission spectrum of PAH mixture, including six emission bands fit to a cubic spline (from Rhoads et al. 1994)

Costs to acquire, operate, maintain

The system described here is a laboratory prototype which will be ruggedized for field deployment in 100 m of water in 1994. A rough estimate of the cost to build a second generation system is ca. $180K including (a) the bottom sensor, (b) 250 m of power/signal cable, and (c) an onboard controller and image acquisition/storage/processing unit. The digital spectral library and Spectral Analysis of REMOTS® Chemistry (SARC) software for spectral analysis are proprietary (SAIC). Required maintenance cost of the sensor system is estimated to be ca. $3K/year. The most expensive expendable is the Hg lamp bulb ($2K), which has a service life of about 2,000 hr.

Technological maturity and risks

The prototype described here is unruggedized and unpackaged for water deployment. The laboratory system has demonstrated proof-of-concept, but no field experience with deployment exists. However, the existing film sediment profile camera system has been demonstrated to be very successful in commercial work around the world for over 20 years. Therefore, the concept of acquiring in situ benthic data by profile imaging is a low risk. The major risk in expanding this technique to chemical measurement is modifying the spectrometer for field conditions and sensor reliability.

Future development requirements

In late 1994 and early 1995, the spectrometer will be ruggedized and packaged for deployment to 100 m. Extensive testing and evaluation will be required during the summer of 1995. Commercial application is anticipated in late 1995. Early tests will be done at open-water dredged material sites in New England.

The UV spectrometer is being developed to measure organic pollutants. A second SAIC internal research and development (IR&D) initiative will be to add a sensor module for measuring contaminant metals within the imaged field. This addition will involve either energy-dispersive X-ray fluorescence (EDXRF) or an array of fiber optic chemical sensors (FOCS).

In addition to the sediment penetrating UV spectrometer described here, a diver-operated prototype UV reflectance spectrometer has been successfully tested in Florida waters to collect spectral signatures of corals. The intention of this application is to relate the spectral signature to coral and zooxanthella physiology and reef condition.

Information sources

Dr. Donald C. Rhoads is the IR&D Project Manager and co-inventor of the Hyperspectral UV Imaging Spectrometer.

Information about the diver-operated coral spectrometer for application to hard substrate conditions may be obtained from the inventor, Dr. Charles Mazel, Massachusetts Institute of Technology (M.I.T.), Cambridge, MA, (617) 253-4349.

Megahertz Acoustic Sled

Sensor name: Megahertz acoustic sled

Sensor category

Nondestructive, in-water and in situ characterization of structure and physical features of sediments and hard bottom, including benthic epifaunal and infaunal organisms, and subsurface sedimentary structures to 10-cm depth.

Description

Acoustic systems have been used for several decades for remote sensing of the water column, ocean bottom, and marine and continental geological structures (Clay and Medwin 1977). These earlier studies used low-frequency sound (10 to 20,000 Hz) to penetrate the water column and subbottom structures. Sound absorption by the water column and subbottom geological structures is frequency-dependent, with low absorption occurring for low-frequency sound sources and high absorption occurring for high-frequency sound sources. The vertical resolution of subbottom structure is determined by the acoustic wavelength and frequency used (see Table 5). The use of high-frequency sound permits resolution of small features and is referred to as ultrasound or ultrasound imaging when it is combined with computerized imaging and image enhancement. Ultrasound (high-frequency sound waves) is now extensively used as a medical diagnostic tool capable of fine spatial resolution, but its application to the study of sediments is in an early developmental stage.

The acoustic system for the Megahertz Acoustic Sled has been lab bench tested (Orr and Rhoads 1982), but the towed sled package is a concept that has not been translated into a field prototype. The system consists of an acoustic array that broadcasts high-frequency, narrow-beam sound waves over the region of interest; in the experimental prototype, a frequency of 1.6 MHz and an acoustic beam width of 2 cm were employed (Figure 9). The laboratory prototype system used a commercially available cardiac acoustic

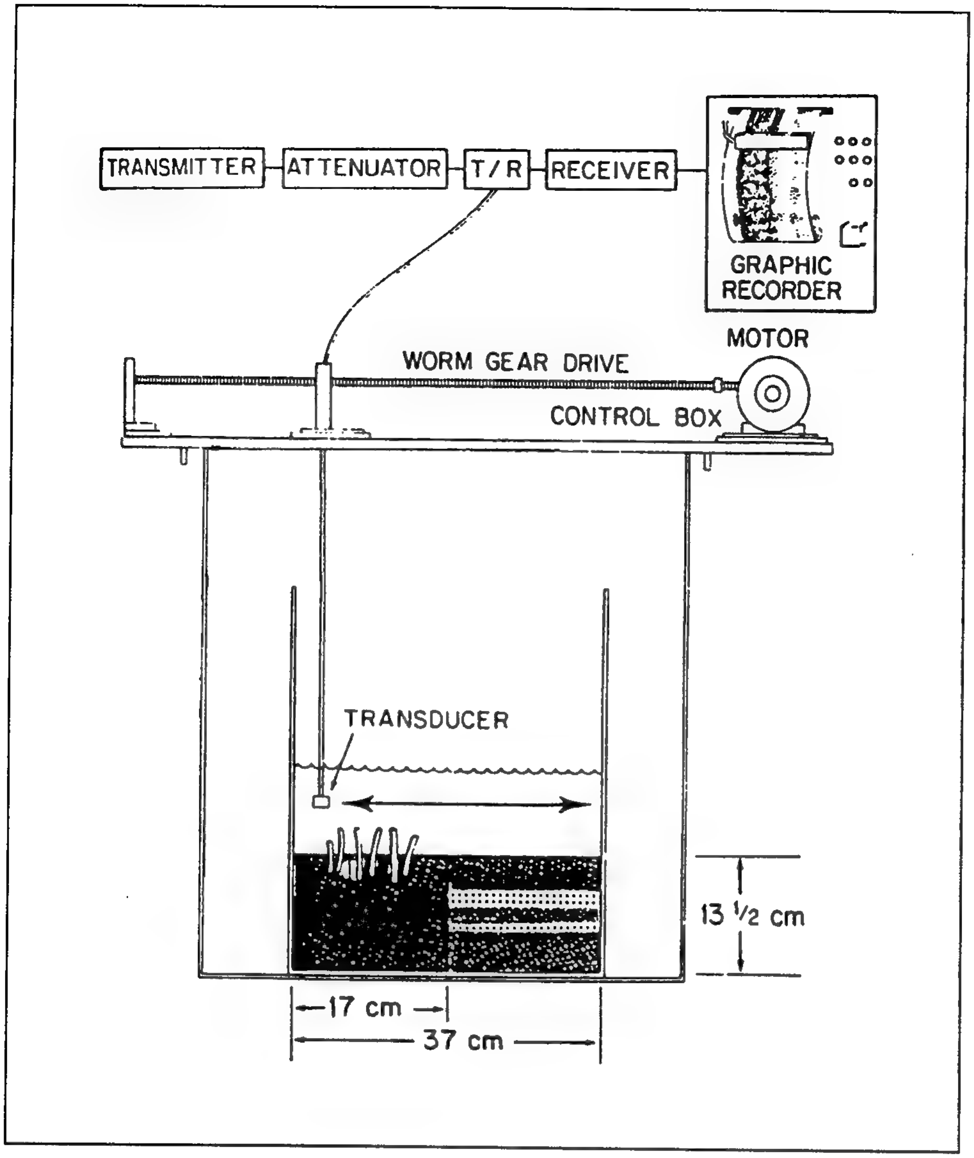


Figure 9. Apparatus and acoustic system used to acoustically scan sediment samples (from Orr and Rhoads 1982)

transducer, resonant at 1.6 MHz (KB-Aerotech, Lewistown, Pensylvania). The transducer was mounted to a nut threaded on a motor-driven worm gear. Backscattered acoustic waves from the sediment-water interface and structures within the sediment reaching the sensors were used to create images of the cross section of material penetrated by the acoustic waves. A Honeywell Model 1856A Visicorder was used for recording.

The end product includes 3-D mapping of sedimentary features over a larger region of interest, down to a depth of 6 to 10 cm; the area covered in this experiment was 5 × 7.5 cm for the fixed-position acoustic array used (Figure 10). The area covered by a towed acoustic sled depends on whether

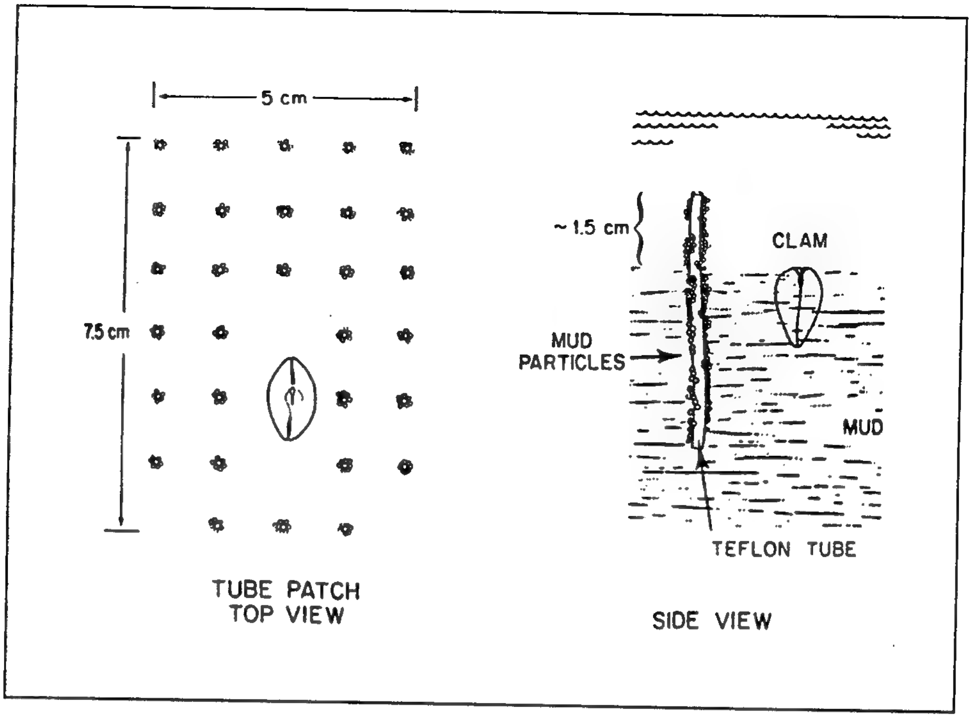


Figure 10. Top and side views of clam position and artificial worm tube patch arrangement (from Orr and Rhoads 1982)

the acoustic beam sweeps or is fixed at a given angle relative to the bottom, and tow speed. Sediment penetration depth is limited by incident pulse energy or transducer voltage and the acoustic absorption/reflection properties of the sediment.

Data output

In the initial study, backscattered acoustic signals from the sediment-water interface and structures within the sediment were amplified and then recorded with a Honeywell Model 1856A Visicorder containing recorder chart paper. Speed of chart paper was adjusted to permit graphic presentation on a 1:1 scale of the horizontal acoustic data. Vertical acoustic data were not at a 1:1 scale because the vertical scale expansion is depth-dependent due to varying sound propagation speed in the sediment.

Examples of sensor/system outputs

Acoustic systems using narrow-beam, high-frequency (MHz) acoustic waves can provide rapid, nondestructive sensing of soft-bottom sediments, hard-bottom, sedimentary fabrics and structures to the depth of several centimeters, distinguishing smooth versus rough topography, sediment resuspension, sediment transport, suspensates, distinguishing benthic organisms and their biogenic structures in sediments (Orr and Rhoads 1982). The resolution

is determined by the ratio of the scale of the mean surface roughness elements to the wavelength of incident sound. Data can be correlated quantitatively with particle or bed roughness scales by appropriate signal processing (Rhoads 1987, Guigné et al. 1993). The upper 10 cm of sediment is the layer in which biological, physical, and chemical processes are most active, and where recent sedimentation, erosion, and early diagenesis occur. An acoustic sensor could be used for high-resolution, spatially extensive surveys of sediment-bottom type, benthic communities of organisms, and sedimentary structures down to a depth of about 10 cm. An example of an acoustically imaged vertical sediment section containing worm tubes is shown in Figure 11, compared with the same section imaged using X-radiography (Figure 12). Acoustic data were also obtained from horizontal surfaces.

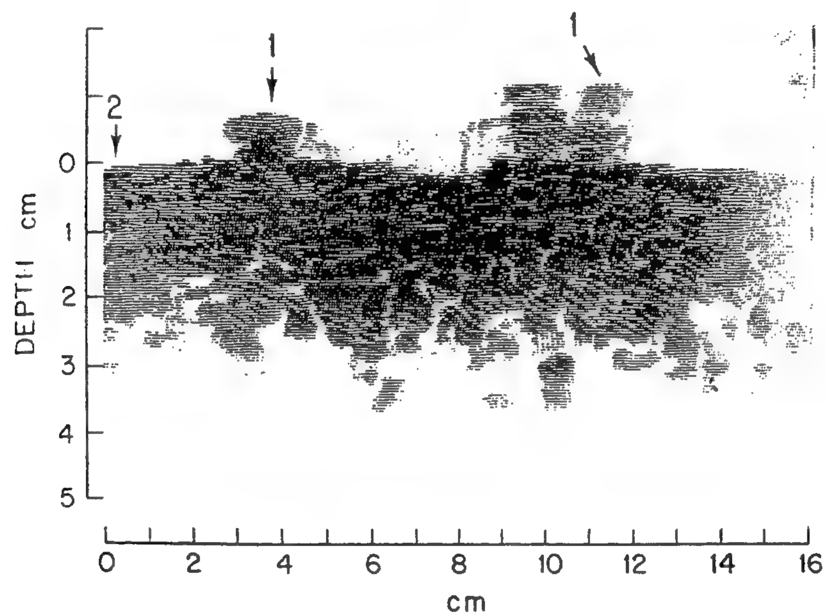


Figure 11. Acoustic image of experimental section, showing artificial worm tubes (1), sediment-water interface (2), and subsurface sediment structure (from Orr and Rhoads 1982)

Costs to acquire, operate, maintain

The cost to build the experimental system are estimated to be approximately $10K.

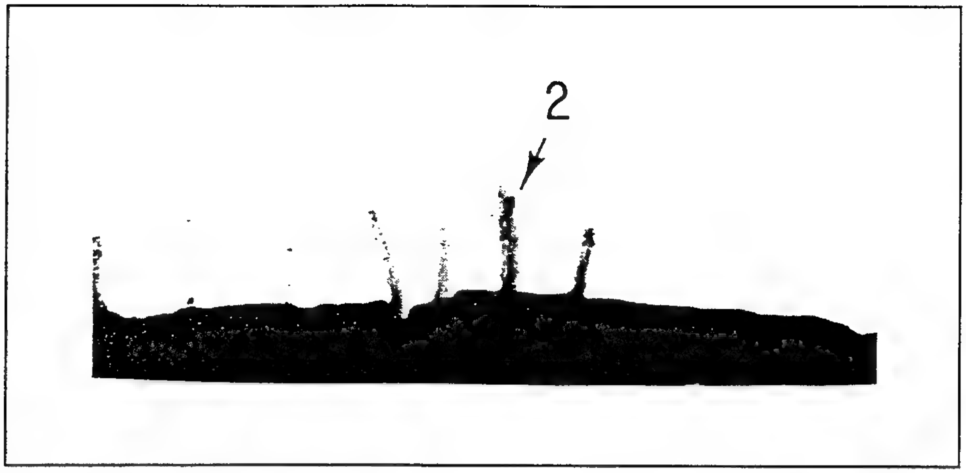


Figure 12. X-radiograph of experimental section, showing artificial worm tubes (2) above sediment-water interface (from Orr and Rhoads 1982)

Technological maturity and risks

The basic acoustic principles and technology have been tested experimentally using marine sediments in a wet lab. The results provide quantitative and qualitative information on sediments, sedimentary features, and benthic organisms (Orr and Rhoads 1982). However, the towed acoustic sled has not progressed beyond the conceptual stage.

Future development requirements

The towed sled housing and shipboard control for the acoustic array require development, as does its integration with navigational and bathymetric sensors. The original work, accomplished in 1980-1981, used state-of-the-art sensors available at the time. In the intervening years, sensors have improved as well as signal processing techniques. The new generation of acoustic transducers, image processing, and signal processing technology should be utilized to revisit this concept, as it is likely that automated data acquisition, processing, and analysis would provide more quantitative results. The acoustic package should have adjustable frequency, as fine-grained muds require a higher frequency beam for penetration, while sand and gravels are penetrated to the same depth by a lower frequency.

Information sources

Dr. Donald C. Rhoads has been directly involved in technology development for this project.

Acoustic SubSeabed Interrogator (ASI)

Sensor name: Acoustic subseabed interrogator (ASI)

Sensor category

On-bottom towed sled, imaging of "acoustic cores" of soft and hard bottoms, including benthic organisms.

Description

This instrument is intended to be an "acoustic corer" to obtain quantitative geotechnical information on a cylindrical volume of sediment, which is then used for computer-aided tomography of soil property parameters. The volume of material that can be covered by a single sampling event is several meters in radius and has a depth equivalent to a conventional geotechnical borehole. The ASI is particularly well suited to studies of complex, heterogeneous sediment layers, including seismically "hard" facies such as glacial tills comprising boulders and cobbles, facies which are opaque to most other seismic profiling systems in use.

With the ASI, 3-D mapping of geophysical parameters of the near subsurface can be carried out with much greater accuracy than is possible with conventional seismic stratigraphic surveying methods, similar to that achieved using the Acoustic Sled previously described. Geophysical parameters that can be measured layer by layer going downcore include compressional velocity, attenuation losses and thicknesses, and absorption coefficients. These measured parameters are then used to infer sediment properties such as grain size (ranging from mud to 3-m-wide boulders), density, porosity, water content, sediment sorting and homogeneity, and presence of soft- or hard-tissue organisms above several millimeters in size. Properties of the water and benthic boundary layer can also be interrogated.

The ASI concept is based on optimizing the criteria of temporal and spatial resolution and of coherence by using broadband, narrow-beam calibrated acoustic sources and fixed receivers on a stationary platform (Figure 13). Broad bandwidth signals permit development of acoustic classifiers of fauna, biogenic structures in sediments, and sediment types. Temporal resolution must be high enough to prevent interference within layers and between thin sediment layers and "point" sources associated with benthic fauna. These requirements are best provided by a short, broadband signal and narrow beam to reduce such interference and result in better signal-to-reverberation ratios when seawater scatters the signal. Resolution is on a millimeter scale; the coherent, high vertical resolution and lack of scatter cannot be attained using commercially available acoustic arrays.

The lab prototype has been tested experimentally by Guigné and colleagues (1989 and 1993). It is intended to be mounted on a grab sampler equipped

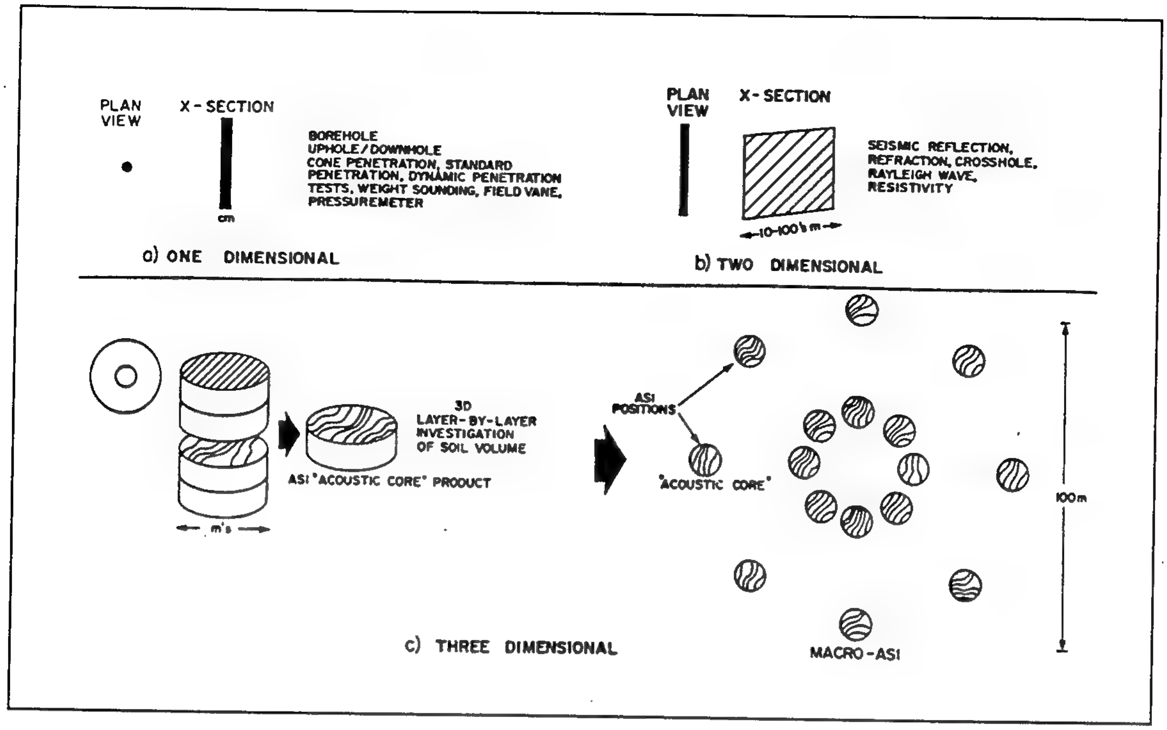


Figure 13. Comparison of conventional and ASI approaches (from Guigné and Chin 1989)

with a high-resolution video camera and eventually to be operated on a bottom-referencing towed instrument vehicle. The broadband, narrow-beam frequency used ranges from 10 to over 200 kHz but is centered on 120 kHz (Guigné et al. 1993). The configuration of inner and outer scanning rings and the instrumental setup are shown in Figures 14 and 15 (Guigné and Chin 1989).

The ASI collects information from a cylindrical volume by mapping compressional velocity and sound attenuation in successively deeper circular scanning areas of several meters in diameter. An inner and outer scanning ring provides a statistical base to distinguish between large sediment grains ranging from mud to boulders (≤ 3 m in diameter). The layer-by-layer interrogation of subsurface slides results in an "acoustic core" or 3-D vertical profile which shows the spatial distribution of geophysical properties of each layer. The acoustic core product can then be compared with conventional geotechnical borehole measurements and seismic stratigraphic records and therefore provides a 3-D ground-truthing approach. It can also be compared with measurements taken at adjacent acoustic "boreholes" to allow mapping along the horizontal plane.

The ASI differs from the Acoustic Sled in greater depth of penetration and less spatial resolution because of the lower frequencies employed.

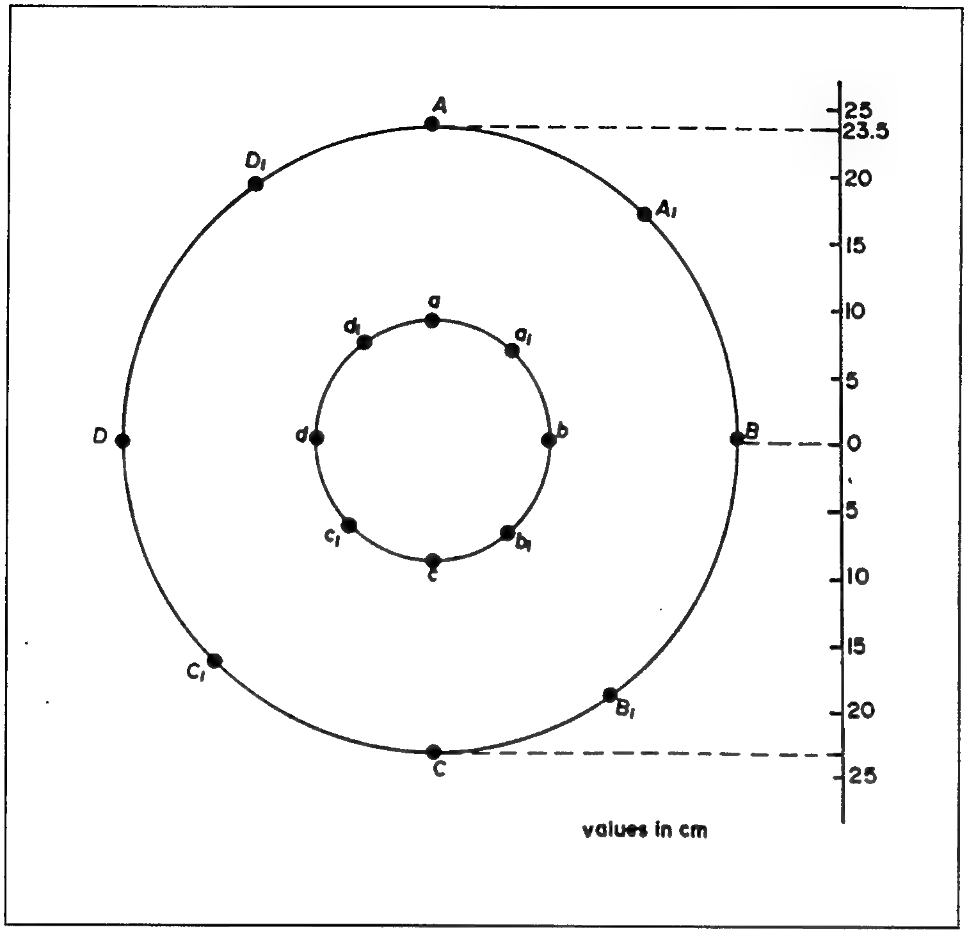


Figure 14. Diagram of outer and inner scanning rings (from Guigné and Chin 1989)

Data outputs

The ASI yields an acoustic core product for layer-by-layer studies of a core-like volume to a depth of several meters, or a 2-D map of the surface plane intersected by the acoustic core, showing the footprints of different ASI positions.

Examples of sensor/system outputs

Examples of output from the ASI include the 3-D acoustic returns (Echo Reduction Frequency Spectra) of a uniform sandy bed (Figure 16) and a flounder in sand (Figure 17). ASI results in 3-D, acoustic isolines, and tabular form are shown in Figure 18. The ASI corer potentially has many uses, such as environmental, disposal site, mining, and natural resource surveys. It is expected to be particularly useful in coastal and nearshore areas or other submarine areas characterized by high kinetic energy, high rates of material

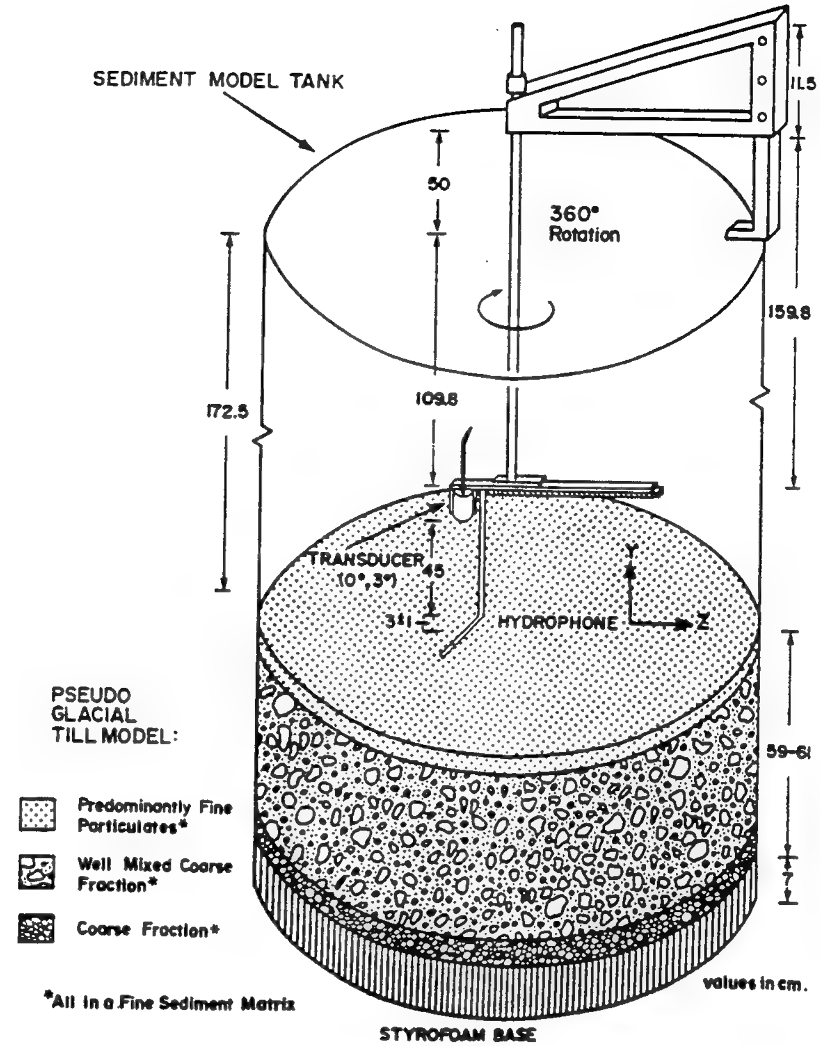


Figure 15. Experimental and tank setup for ASI (from Guigné and Chin 1989)

transport, submarine erosion, or slumping, where boulders or complex mixtures of boulders and fine sediments are likely to be encountered. Biota and sediment type can be distinguished using discrete frequency-dependent signatures, and the echo reduction (ER) of an organism is defined in terms of complex incident and reflected sound pressures. The geophysical properties and structure of sediment in a cylindrical volume, including thickness and stratigraphy of complex, heterogeneous soft-bottom sediment layers, may be determined.

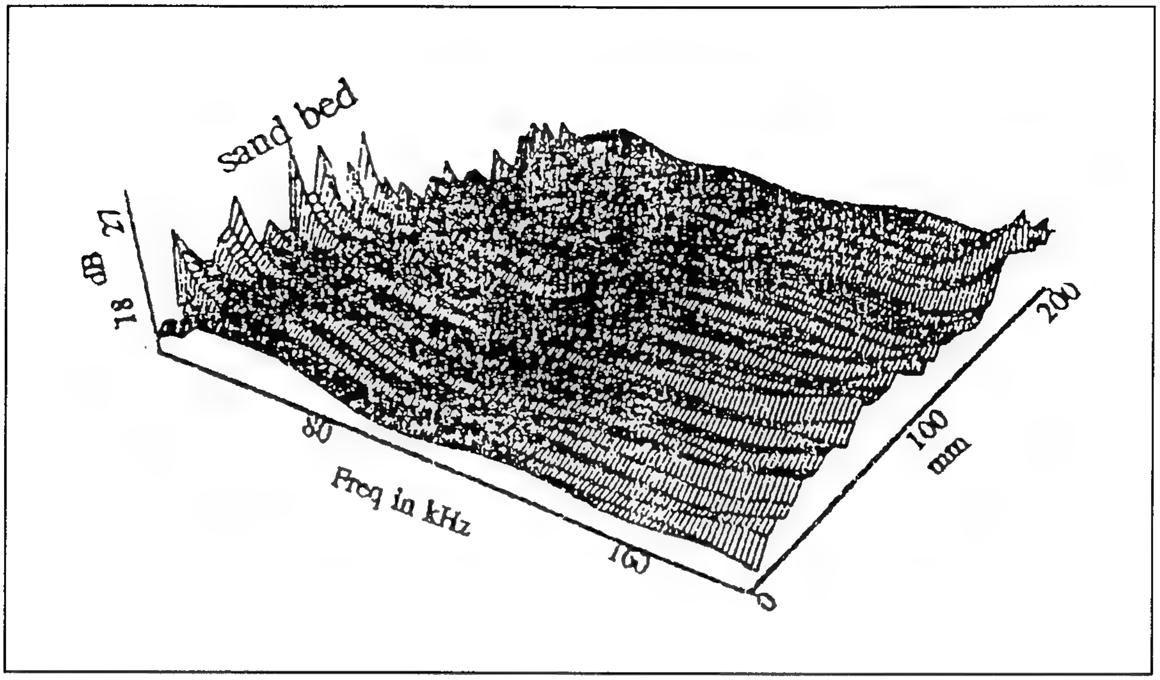


Figure 16. ASI echo reduction of a uniform sand bed (from Guigné et al. 1993)

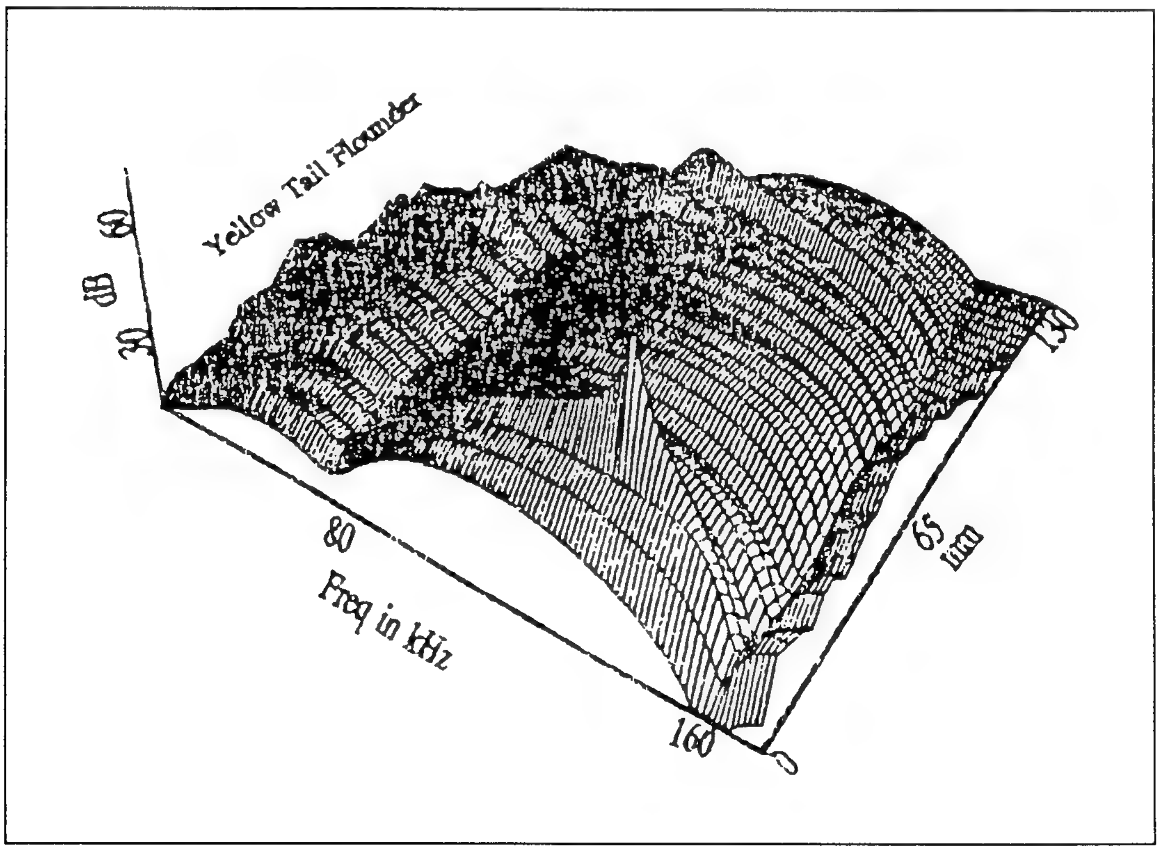
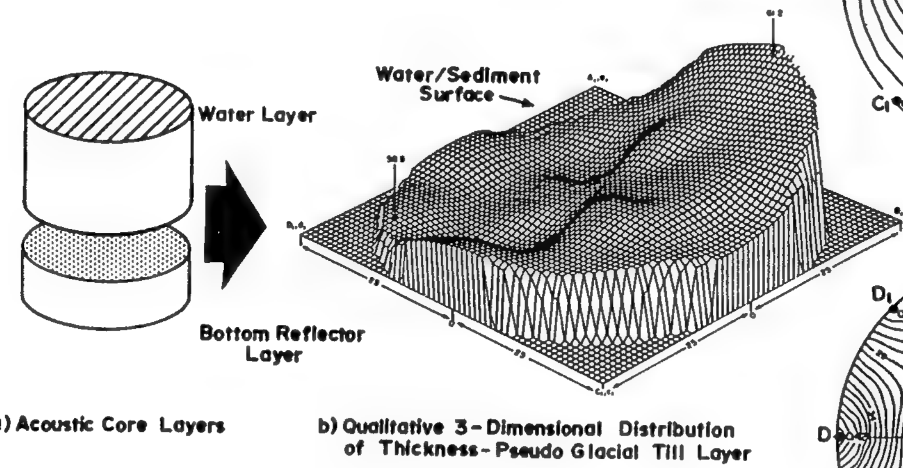


Figure 17. ASI echo reduction frequency spectra from a line profile across a yellowtail flounder (*Limanda ferruginea*) (from Guigné et al. 1993)

VELOCITY				
Velocity Indices	[%]	Comparison Types	Deviation S [m/s]	Ave. Velocity [m/s]
$\psi_{c,1}$	16.9	Outer ring only	35.9	1983.9
$\psi_{c,2}$	33.1	Inner ring only	22.1	1968.4
$\psi_{c,3}$	32.6	Between outer & inner rings	22.4	n/a
$\psi_{c,4}$	22.4	Acoustic core: outer+inner	29.9	1976.2
$\psi_{c,5}$	69.3	0° and 3° transmissions	7.3	n/a



ATTENUATION COEFFICIENT (κ)				
Attenuation Indices	[%]	Comparison Types	Deviation S [dB/m·kHz]	Ave. Attenuation [dB/m·kHz]
$\psi_{a,1}$	15.7	Outer ring only	0.074	0.24
$\psi_{a,2}$	37.7	Inner ring only	0.039	0.25
$\psi_{a,3}$	20.7	Between outer & inner rings	0.063	n/a
$\psi_{a,4}$	24.1	Acoustic core: outer+inner	0.057	0.25

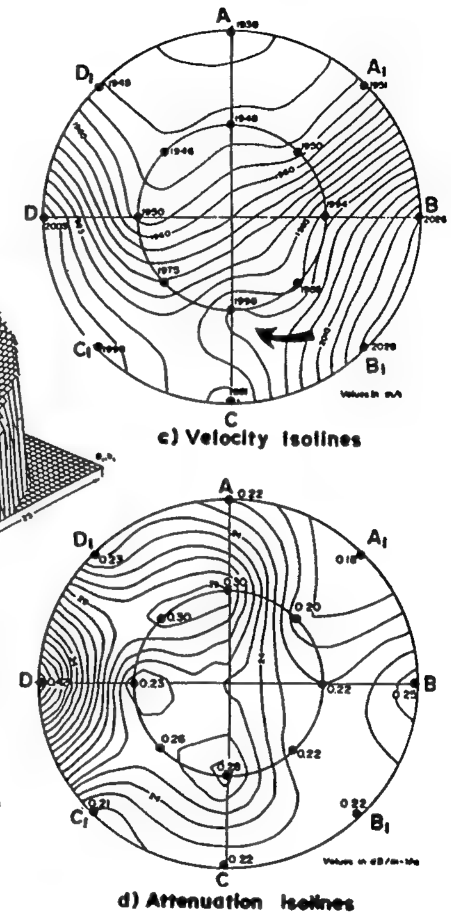


Figure 18. ASI results in 3-D, acoustic isolines, and tabular form (from Guigné and Chin 1989)

Costs to acquire, develop, maintain

The custom-designed ASI was developed for research purposes, but it is intended to be developed for widespread application by Guigné International Ltd. (GIL). It consists of a parametric array transducer designed by GIL and a Brüel and Kjær 8103 cylindrical hydrophone mounted in vertical stainless steel tubes held in a rack and driven by a worm gear device. A movable aluminum rack holds the acoustic sensors in accurate alignment. Acoustic data are processed using GIL's *SONIQUE^{cm}* software to distinguish macrobenthos. Information on costs of the system were not available at the time of preparation of this review.

Technological maturity and risks

The ASI exists as a one-of-a-kind prototype of the acoustic system which has been used in lab and mesocosm experiments. The acoustic system prototype is intended to be mounted on a grab sampler equipped with video camera for conventional video imaging of the bottom. The towed sled ASI is in the conceptual stage at this time. The technological maturity is low; the system has not been tried, to our knowledge, in actual marine or lacustrine environments.

Future development requirements

Considerable development would be required to incorporate the prototype instrument into a working commercial package, as well as to design, build, deploy, test and operate the acoustic array on a towed instrument vehicle with bottom-referencing capability.

Information sources

Jacques Guigné, whose address is Guigné International Ltd., 82 St. Thomas Line, Site 21, Box 13, RR#1, Paradise, Newfoundland, A1L 1C1, Canada, is the principal investigator who developed the ASI.

3 In-Water Sensors

Laser Line Scan System (LLSS)

Sensor name: Laser Line Scan System (LLSS)

Sensor category

In-water towed, remote sensing of bottom topography and detailed features of soft- and hard-bottom seafloor, using laser imaging in near real-time.

Description

Historically, rapid mapping of oblique "panoramic" views of the seafloor were exclusively done by towed acoustic side-scan. Object resolution of a 50-kHz acoustic side-scan is on the order of ≥ 100 cm. The LLSS has been integrated with a conventional Oceanographic Research Equipment ORE 50-kHz side-scan sonar (the Underwater Laser Imaging Survey/Inspection System or ULISIS, Figure 19) for application to disposal site surveys (Hellemn, Fredette, and Carey 1994). The operational concept of the LLSS is depicted in Figure 20. The use of a towed 2-W Argon laser operating in the blue-green spectrum (output mainly at 488 and 514 nm) yields superior, picture quality images with optical resolution in the range of a few millimeters to centimeter-sized objects. The sensor can be towed at speeds up to 6 knots in water depths to 690 m at an altitude of 2.5 to 39 m above the bottom depending on ambient turbidity. Light backscatter in turbid environments is minimized by the small single point of coherent light moving across the bottom. The LLSS extends the imaging range by a factor of 2 to 3 over conventional video imaging.

The bottom image is built up from a rapidly acquired series of spots on the seafloor, each sequentially illuminated by a laser beam about as wide as the diameter of a pencil. The user can select the desired resolution from 512, 1,024, or 2,048 pixels across a fixed 70-deg field of view. The video signal has a dynamic range of 72 db (12 bit). Data are transmitted top-side via

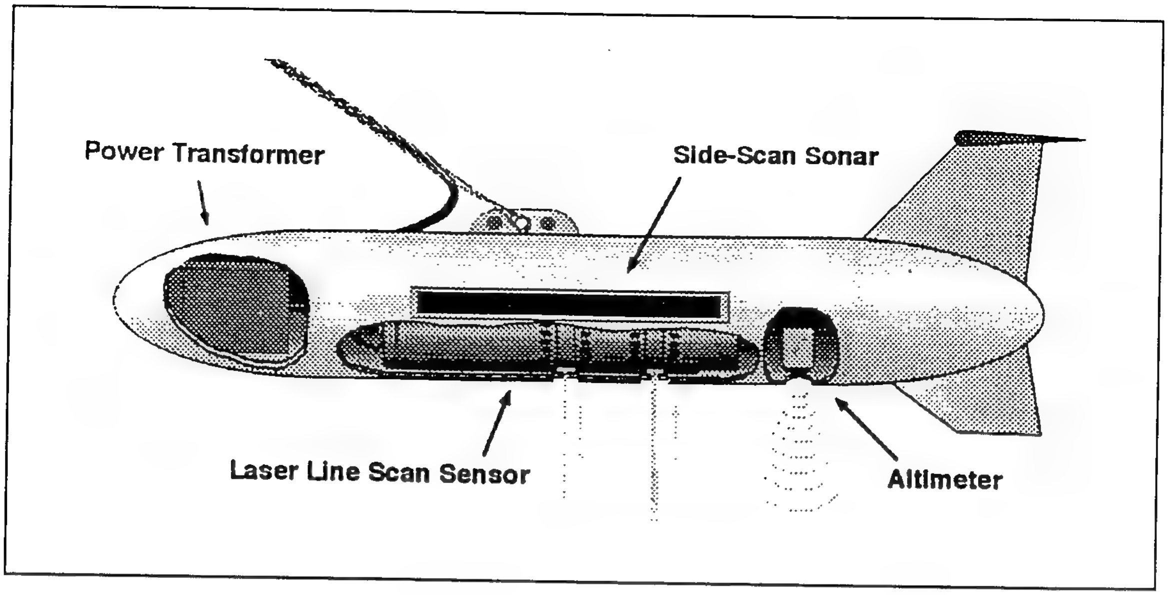


Figure 19. ULISIS vehicle used in the DAMOS survey (Prototype fish is 4 m long and weighs 500 kg)

fiber-optic cable, and the data can be postprocessed from Super VHS analog video tape as well as 8-bit continuous and 12-bit "snapshot" digital data. Onboard equipment also includes a control console for all system functions and visual displays of sensor status data and video data. The major benefit of the optical scanning system relative to traditional acoustic imaging is the higher optical resolution.

Data outputs

The range of applications for the LLSS is similar to that for towed acoustic side-scans except that the order-of-magnitude greater optical resolution of the LLSS allows for better object discrimination and identification (Figure 21). Data output consists of picture quality panoramic analog SVHS video or digital image mosaics of the seafloor. These "lasergrams" are useful for surveying of both soft- and hard-bottom habitats. The footprint of dredged material can be mapped as well as sediment type, bottom dwelling fish, crabs, lobsters, and dumped structures such as waste barrels. The high optical resolution of the LLSS often allows taxonomic identification of imaged organisms; therefore, this technology has potentially important applications for fisheries resource assessment. The major disadvantage of the system is that the swath width is narrower than for acoustic side-scans, and in its present configuration, it is large and heavy so mobilization/demobilization and shipping costs are high. Optical performance is compromised by platform instability and water turbidity. In turbid water, the sensor must be towed close to the bottom limiting search area and increasing the likelihood of colliding with objects protruding above the bottom.

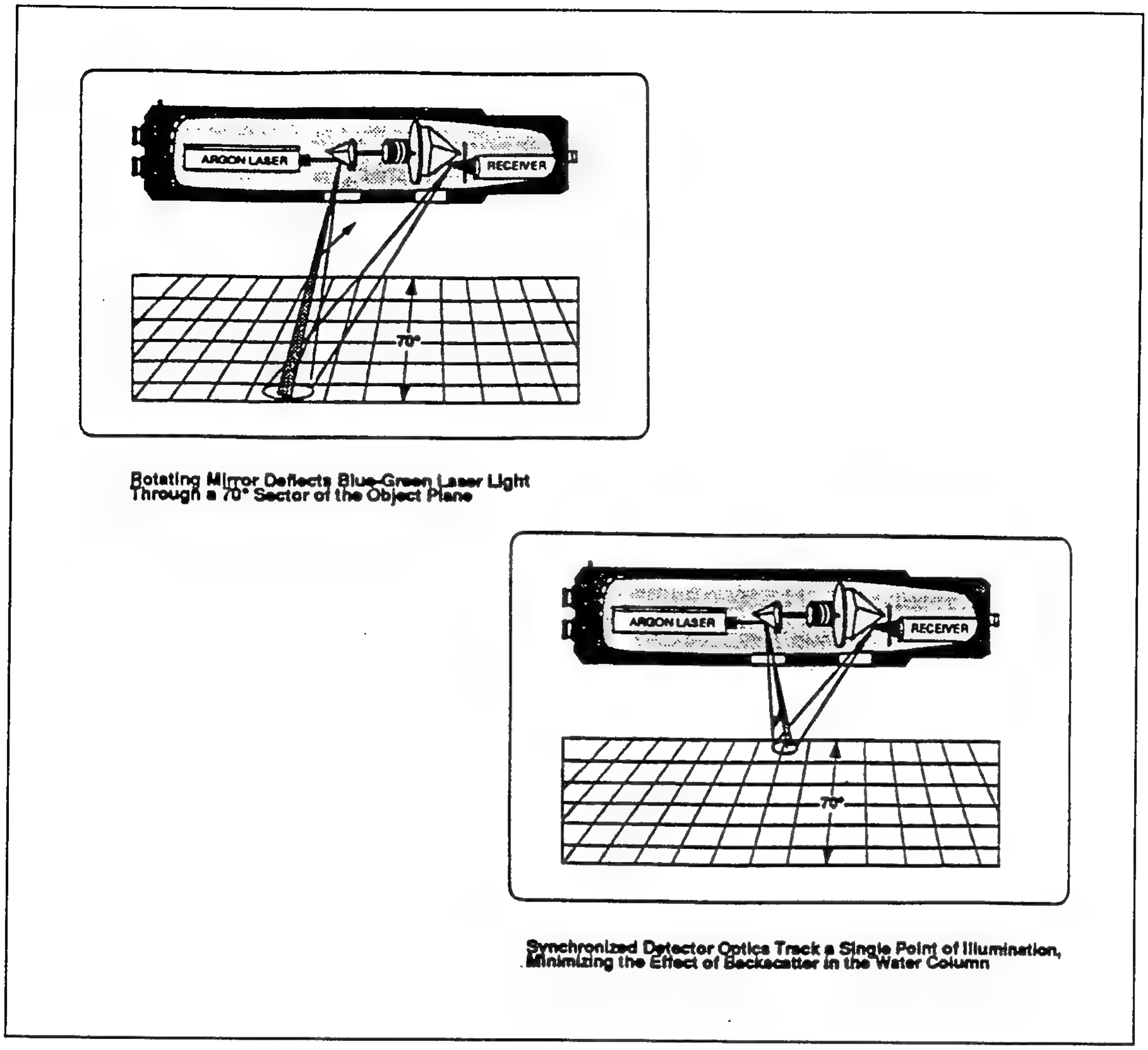


Figure 20. Operational concept for laser line scan sensor

Examples of sensor/system outputs

Examples of LLSS output are shown in Figures 21-23.

Costs to acquire, operate, maintain

The prototype system represents a joint venture between Westinghouse Underwater Laser systems and SAIC. Westinghouse owns the tow fish sensor (SM2000), and SAIC provides all top-side control/recording equipment including navigation. To date, a turn-key cost for the system has not been prepared, but the system can be rented with operators. The size and weight of the prototype system (Figure 19) complicates logistics and requires a large survey vessel and support crew.

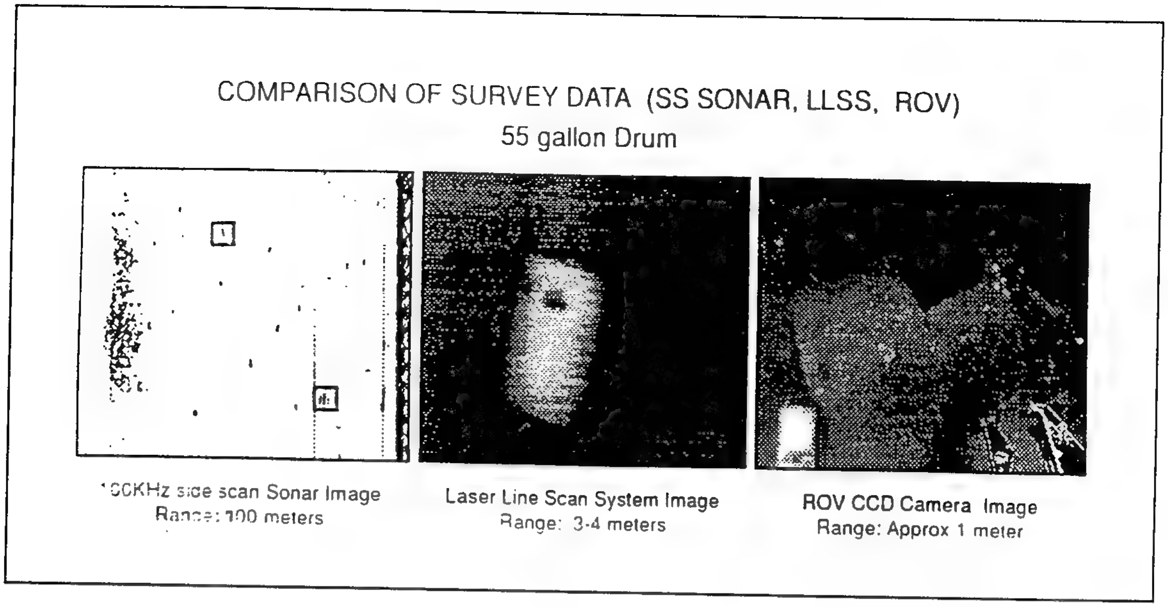


Figure 21. Comparison of side-scan sonar, laser line scan system, and conventional remotely operated vehicle (ROV) CCD camera imaging of a 55-gal drum, Industrial Waste Disposal Site, Massachusetts Bay (from Hellemn, Fredette, and Carey 1994)

Technological maturity and risks

The technology is now in the demonstration phase. Demonstrations have been made in oceanic waters off San Diego, the Gulf coast, and in New England waters. The system is also being used in the Mediterranean. Technology risk is low for the prototype.

Future development requirements

Miniaturization of the system will be required to reduce mobilization, deployment, and demobilization costs.

Information sources

Dr. Drew Carey, whose address is Science Applications International Corporation (SAIC), 221 Third St., Newport, RI 02840, (401) 848-4770, was involved in the demonstration of results presented in Hellemn, Fredette, and Carey 1994.

Figure 22. LLSS image of debris field with epifauna off San Diego (from Mooradian et al. 1993)

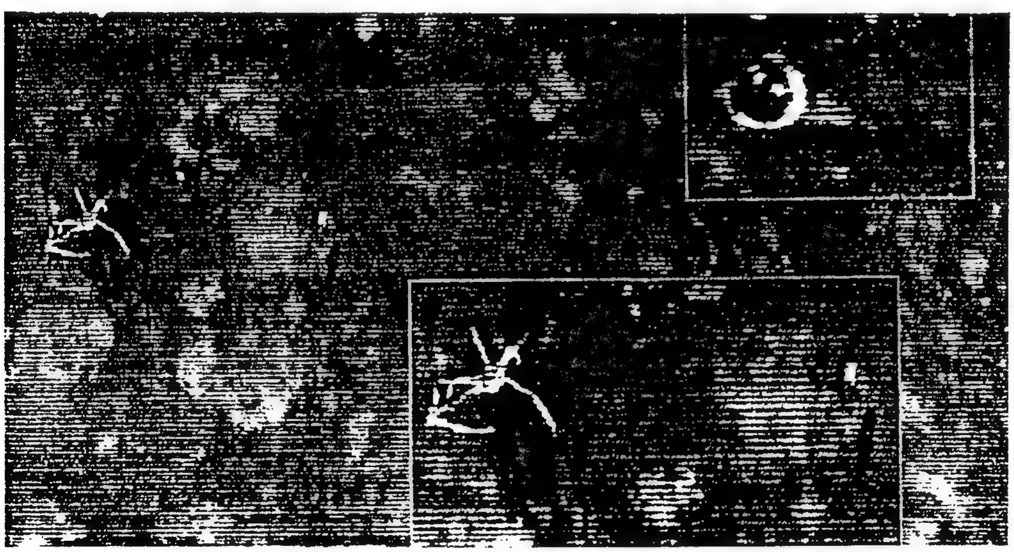


Figure 23. LLSS image of spider crab on mottled bioturbated sediment near Chemosynthetic Site, Gulf of Mexico (from Mooradine et al. 1993)

Gamma Isotope Mapping System (GIMS)

Sensor name: Gamma Sled, or Gamma Isotope Mapping System (GIMS)

Sensor type

In-water, in situ characterization of sediment and lithology, soft and hard bottoms.

Description

The GIMS, or gamma sled, is a rapid surveillance system that uses natural radiation emanating from seafloor, lake-bottom, or river-bottom sediments to interpret lithology and to survey mineral deposits. It was developed by the Center for Applied Isotope Studies (CAIS) at the University of Georgia, Athens, as part of an integrated sediment and water column surveillance system that includes the Continuous Sediment Sampling System (CS^3) and the Water Quality System (WQS) for mapping seafloor mineral deposits and environmental assessment.

The GIMS is a seafloor sled that is remotely deployed and lowered to the bottom, using a winch and A-frame. An underwater gamma radiation detector measures the natural radiation of the bottom (Figure 24). The maximum depth of measurement of gamma radiation is 25 cm. The total gamma radiation activity and the radiation from three naturally occurring isotopes of bismuth, potassium, and tantalum (Bi-214, K-40, and Tl-208, respectively) are used to distinguish between phosphatic sediments (Bi-214), heavy mineral sands (Tl-208), and clay sediments (K-40), either through use of the individual isotopes or their ratios to one another.

A coaxial cable transmits the signal from the detector to the surface shipboard electronics package. The shipboard electronics package contains a portable computer, Loran/Global Positioning System (GPS), fathometer, printer, plotter, and spectrometer. A battery pack is housed in the sled and provides up to 14 days of continuous operation. The spectrometer measures the individual activities of the three separate isotopes (Bi-214, K-40, and Tl-208) and the total gamma activity in counts per minute (CPM). Precruise calibration is done while traveling to the sampling site, by obtaining a gamma radiation spectrum of a thorium-rich monazite sand sample used as a standard; postcruise calibration is also done to verify correct operation of the instrumentation and calibration procedures.

Considering the work requested, the sled can be towed at 3 to 5 knots, depending on condition of seas, in a line or grid; grid spacing is usually 305 m between transects for mapping reconnaissance of an unknown area. If a single survey line is used, the mapping technique can be employed only

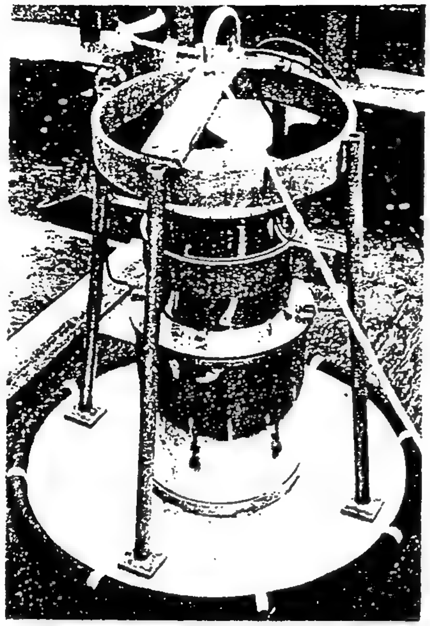


Figure 24. Underwater gamma-ray detector used in gamma sled (Stainless steel container house Ge(Li) detector, preamplifier, and cryogenic reservoir. Detector is electrically connected to surface ship by coaxial cable)

if multiple linear transects are done. The sled is commonly towed 100 to 150 nautical miles during a 24-hr period.

Data outputs

Output data include strip-chart recordings of gamma radiation plotted at 60-sec intervals and 2- and 3-D maps of gamma activity which can be used to infer distribution of sediments of different lithologies. Ancillary data recorded include time, latitude, and longitude. A 24-hr format is used to acquire and store data until the region to be surveyed is finished. Output is printed every 60 sec to paper and to computer diskette, and any of the four isotopic parameters can be tracked by monitoring false-color intensity levels on the plotter.

Examples of sensor/system outputs

Examples of strip-chart recordings of gamma radiation activity of seafloor sediments, marine phosphate deposits, and marine heavy mineral deposits are shown in Figures 25, 26, and 27. An example of a 2-D contour map of K-40 activity for a Pensacola, Florida, survey and a 3-D topographic profile of the gamma activity are shown in Figure 28. These maps permit determination of seafloor lithologic patterns and allow pinpointing of stations for further ground-truthing of lithology.

The gamma sled has been successfully used to map phosphate and heavy mineral deposits off the Georgia and Florida coasts and in monitoring ocean-dredged material disposal sites (ODMDS). It has been used in conjunction with sediment profiling imagery to infer distribution of disposed sediments

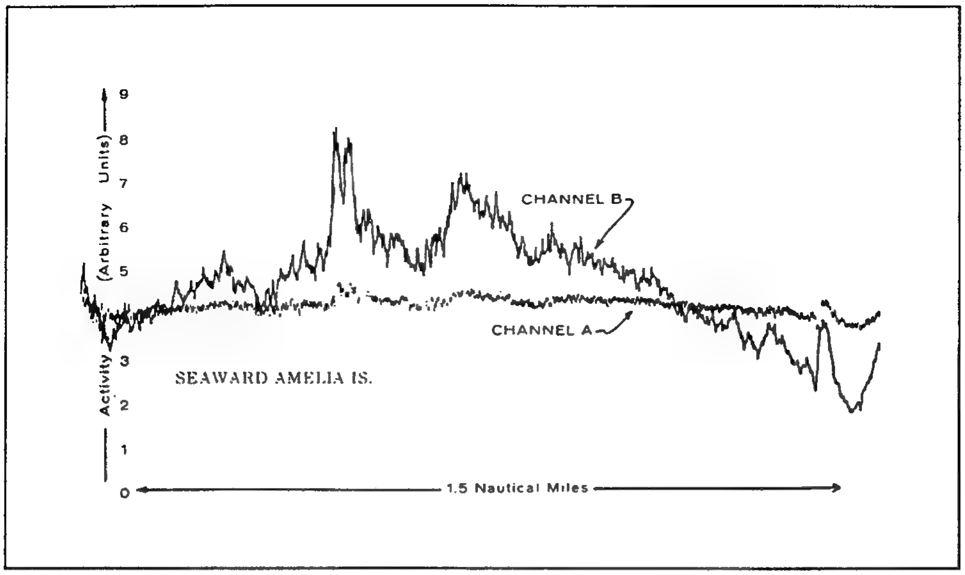


Figure 25. Radiometric measurements of seafloor sediments, taken with towed gamma sled off Amelia Island, Florida (Data were recorded on a dual-channel strip chart) (from Noakes, Harding, and Spaulding 1974)

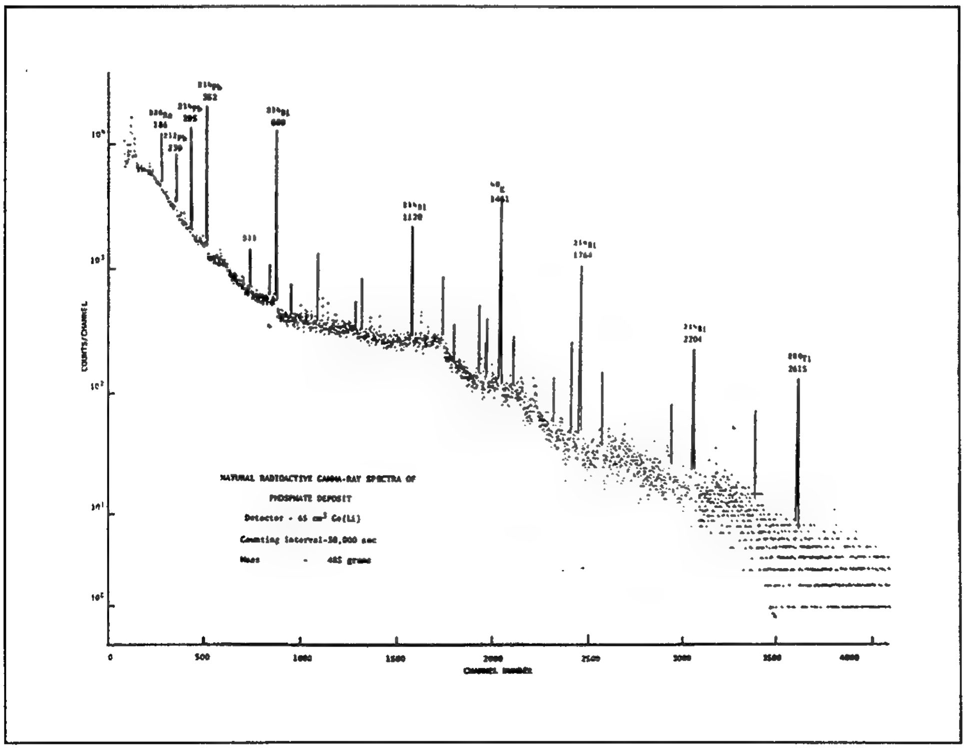


Figure 26. Example of gamma ray spectrum of marine phosphate rock, taken with underwater gamma detector in the laboratory (from Noakes, Harding, and Spaulding 1974)

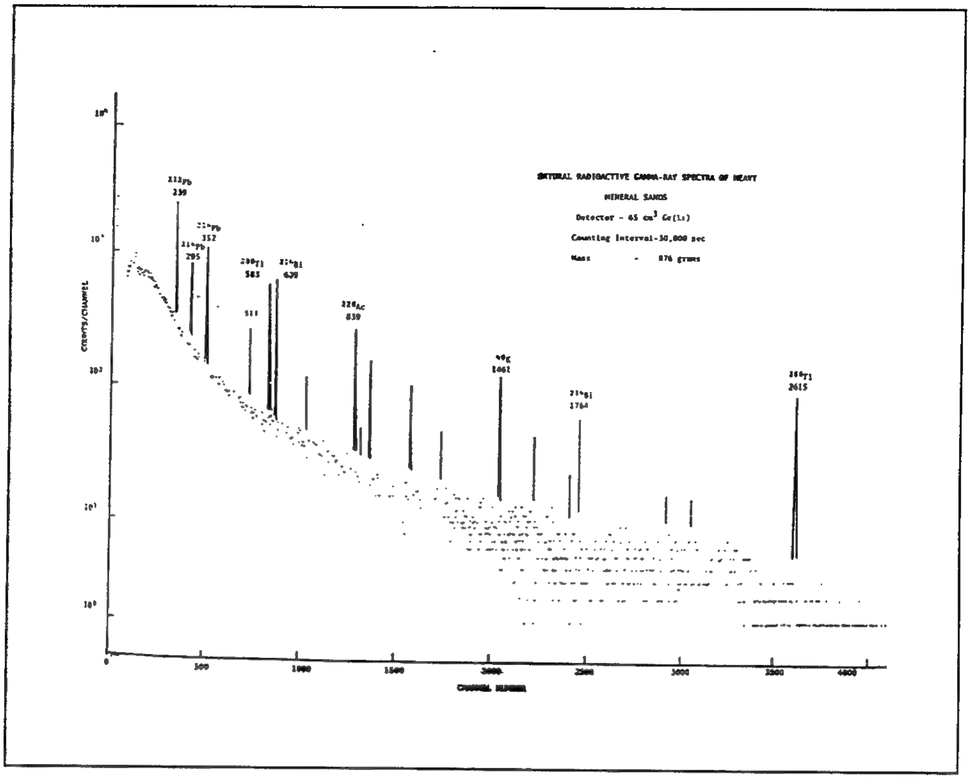


Figure 27. Example of gamma ray spectrum of marine heavy mineral sand made with underwater gamma detector in the laboratory (from Noakes, Harding, and Spaulding 1974)

from harbors that typically have gamma fingerprints different from those of open shelf sediments (Rhoads 1990).

Costs to acquire, operate, maintain

The gamma sled was developed by the CAIS at the University of Georgia, and it is maintained as a research instrument. It can be hired out for ocean surveys, either singly or simultaneously with the CS^3. If it is hired singly, then the costs, as of October 24, 1994, are as follows: (a) four-person crew at $400/person/day, including travel time to and from Athens, Georgia; (b) GIMS at $2,000/day of operation; (c) box core: $500 for analysis of each box core, including XRF, gamma activity, and particle size; (d) report, at $4,000 for GIMS survey report; and (e) travel, including costs of a four-person crew at $75/person/day per diem, shipping and transportation costs, and mileage for vehicle use at $0.28/mile.

If both the GIMS and the CS^3 are hired for simultaneous sled survey work, then the costs are as follows: (a) five-person crew at $400/person/day, including travel time from and to Athens, Georgia; (b) joint use of GIMS/CS^3

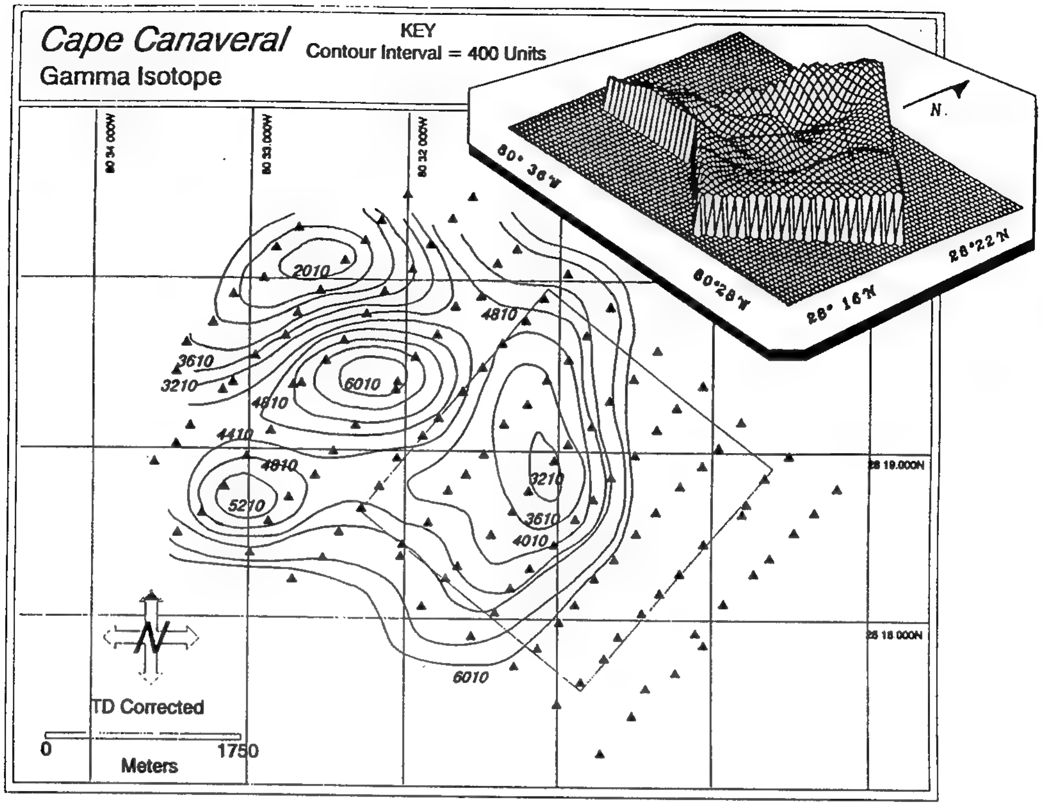


Figure 28. Example of 2-D and 3-D gamma isotope maps of Cape Canaveral dredged material disposal site (from Rhoads 1990)

at \$4,000/day of operation; (c) CS^3 XRF analyses of CS^3 wafers at \$20/filter; (d) \$500 for analyses of each box core, including XRF, gamma activity and particle size; (e) \$6,000 for GIMS/CS^3 survey report; (f) travel costs of five-person crew at \$75/person/day per diem; and (g) shipping and transportation costs and vehicle mileage.

Technological maturity

The gamma sled is technologically mature in academic research and has produced published results for at least a decade. Commercially, however, it would require development, testing of the package, possibly some minor redesign, and production.

Future development requirements

The gamma sled would probably require some redesign for mass production and commercial packaging. Improvements could be made in imaging technology and real-time display of results.

Continuous Sediment Sampling System (CS^3)

Sensor name: Continuous Sediment Sampling System (CS^3) Sled

Sensor type

In-water and in situ characterization of sediment composition of soft bottoms and associated near-bottom turbidity (benthic boundary layer, mud blanket), using an automated in situ sediment collector, followed by land-based energy-dispersive X-ray fluorescence (EDXRF).

Description

The CS^3 includes a towed sled, shipboard processor, shipboard electronics, and land-based EDXRF instrumentation for nondestructive elemental analysis of sediments. The CS^3 is part of an integrated water and sediment surveillance system which includes the GIMS, or gamma sled, and the WQS for mapping seafloor mineral deposits and environmental assessment. It was developed by the CAIS at the University of Georgia, Athens, Georgia.

The CS^3 sled is a cylindrical stainless steel mesh housing, which is 1 m long by 25 cm in diameter. It houses a submersible Delrin plastic pump that pumps a slurry of suspended sediment from the seafloor, through a 1-in. (2.54 cm) (ID) rubber hose, to a centrifugal cone that separates the fine-grained sediment fraction (silt fraction $\leq 63\ \mu m$) from the sand fraction; the latter is discarded because contaminants are most likely to be concentrated in the silt fraction. Portions of the fine-grained sediments are sampled onto glass fiber filters, numbered, and stored for transportation to the land-based EDXRF for elemental analysis. The maximum operational depth of the CS^3 sled is approximately 50 m, using 150 m of hose. Hose length is adjusted according to bottom depths by coupling sections together with quick connectors. The sled is deployed when approaching the survey site and towed at about 3 knots.

The XRF spectrometer is a land-based laboratory unit, not yet integrated with shipboard components. The package is approximately $1.0 \times 1.0 \times 1.5$ m in size and weighs approximately 50 kg. The land-based EDXRF allows for rapid data generation combined with secondary target excitation for very low elemental detection limits that are not achievable with conventional

energy dispersive systems. The XRF is capable of analyzing about 80 different elements, but a typical elemental analysis only includes 20 to 25 elements comprising major oxide-forming elements, heavy metals of environmental and economic importance, and transition elements. Quality control is ensured through calibration using a standard. Analysis times depend on the number of elements analyzed but can range from 60 min to as long as 15 hr.

Data outputs

Data output includes combined survey and elemental concentration data, which are used to produce 2-D and 3-D maps of elemental distributions to interpret seafloor lithology in the survey region. Elemental data are stored in a computer file and combined with the survey data.

Examples of sensor/system outputs

Figure 29 shows an example of the graphical output from the CS^3 sled XRF elemental analysis. The upper figure is a 2-D contour map of the concentration distribution of aluminum, and the lower figure is a 3-D topographical representation of aluminum concentrations. Applications include mapping potential dredging and dredged material disposal sites, disposal site footprints, and dispersal of metal contaminants and sediments from disposal sites.

Costs to acquire, operate, maintain

The CS^3 is maintained as a research instrument at the CAIS, University of Georgia, Athens, Georgia. It can be hired out for ocean surveys, either singly or simultaneously with the GIMS (see previous discussion for combined costs). If it is hired singly, then the costs, as of October 24, 1994, are as follows: (a) four-person crew at $400/person/day, including travel time to and from Athens, Georgia; (b) CS^3 at $2,000/day of operation; (c) CS^3 XRF analyses of CS^3 wafers at $20/filter; (d) box core: $500 for analysis of each box core, including XRF, gamma activity, and particle size; (e) CS^3 survey report, $4,000; and (f) travel, including costs of a four-person crew at $75/person/day per diem, shipping and transportation costs, and mileage for vehicle use at $0.28/mile.

Technological maturity and risks

The CS^3 sled has been in research use for several years. It is judged to be technologically immature in terms of the turn-around time needed for sample analysis.

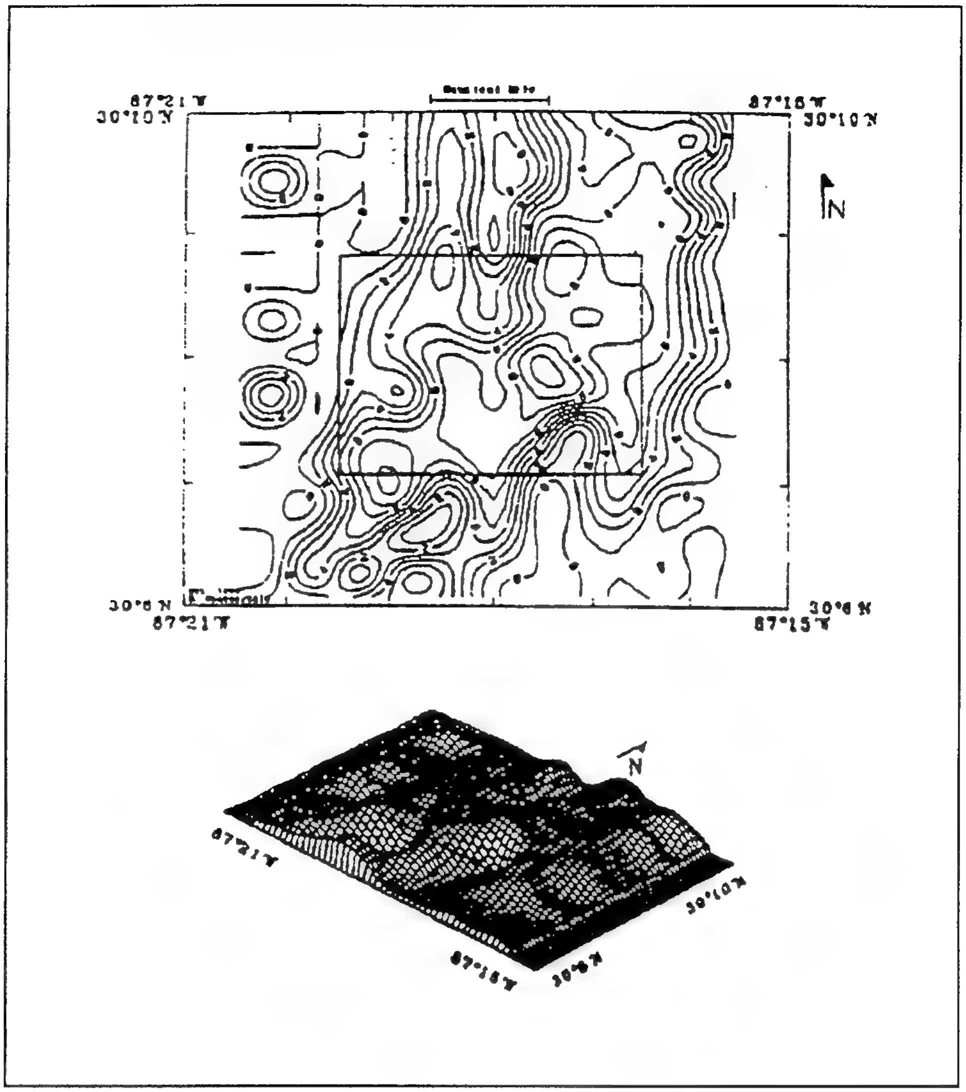


Figure 29. A 2-D contour map (upper figure) and 3-D topographical profile of aluminum concentrations in percent dry weight for the Pensacola, Florida, Offshore ODMDS (from Noakes et al. 1992)

Future development requirements

For real-time use of the XRF in the CS^3 system, a ship-based XRF is required. However, since analytical times vary between 1 and 15 hr for a maximum of 25 elements, real-time use would mean that samples could still be collected faster than they could be analyzed, unless a multiple-sample XRF analysis is possible. Therefore, an alternative faster method of characterizing the elemental composition is desirable.

Acoustic Side-Scan Sonar

Sensor name: Acoustic Side-Scan Sonar

Sensor category

In-water, towed mapping of large-scale bathymetry and benthic features (hard and soft bottoms, large marine organisms or schools).

Description

Acoustic side-scan sonar systems operate in the acoustic frequency range of tens to hundreds of kHz. They provide survey systems capable of wide-swath search and mapping, high-resolution imaging and swath bathymetry. There are a growing number and variety of acoustic side-scan sonar systems, which are reviewed by their type of technology rather than by specific systems or vendors. Side-scan sonar can be used for deep and shallow water surveys in two different modes: (a) high swath/low resolution, and (b) high resolution/ low swath. High-swath, lower resolution surveying maximizes area coverage to rapidly detect possible targets and provide secondary data such as bottom shape and roughness. High-resolution, lower swath side-scan systems provide finer scale imaging and swath bathymetry data for closer target inspection. Secondary data collection such as swath bathymetry is necessary in rougher undersea terrain in order to avoid bottom collisions, particularly when high-resolution surveys are being conducted at towing altitudes near the bottom. The configuration of a side-scan sonar system, including the uncorrected return signal, is shown in Figure 30.

Side-scan sonar systems use acoustic backscatter from the seafloor to produce images of seafloor structural details and roughness. Swath mapping side-scan sonars use twin acoustic beams to generate backscattered signals or successive "pings" constituting data over a broad swath, across-track, which is divided into data points numbering from hundreds to thousands. The along-track pattern of accumulated backscatter pings is accumulated into picture elements or pixels to form a sonograph display; horizontal resolution is limited by the size of the individual pixels. Because the spherically spreading beam hits the seafloor at a high incident angle, there is often a small gap in data directly below the instrument, known as a nadir.

System control is ship-based, including system power, controls, system input/output, and telemetry channel transceivers. In newer systems, system control is often automated to adjust parameters for specific survey requirements and bottom conditions: examples of tuneable parameters include transmit rates, pulse length, gain, or bandwidth (Acoustic Marine Systems (AMS)-120 or Klein 50/500). Attenuation of acoustic energy is compensated for by electronic design and data processing.

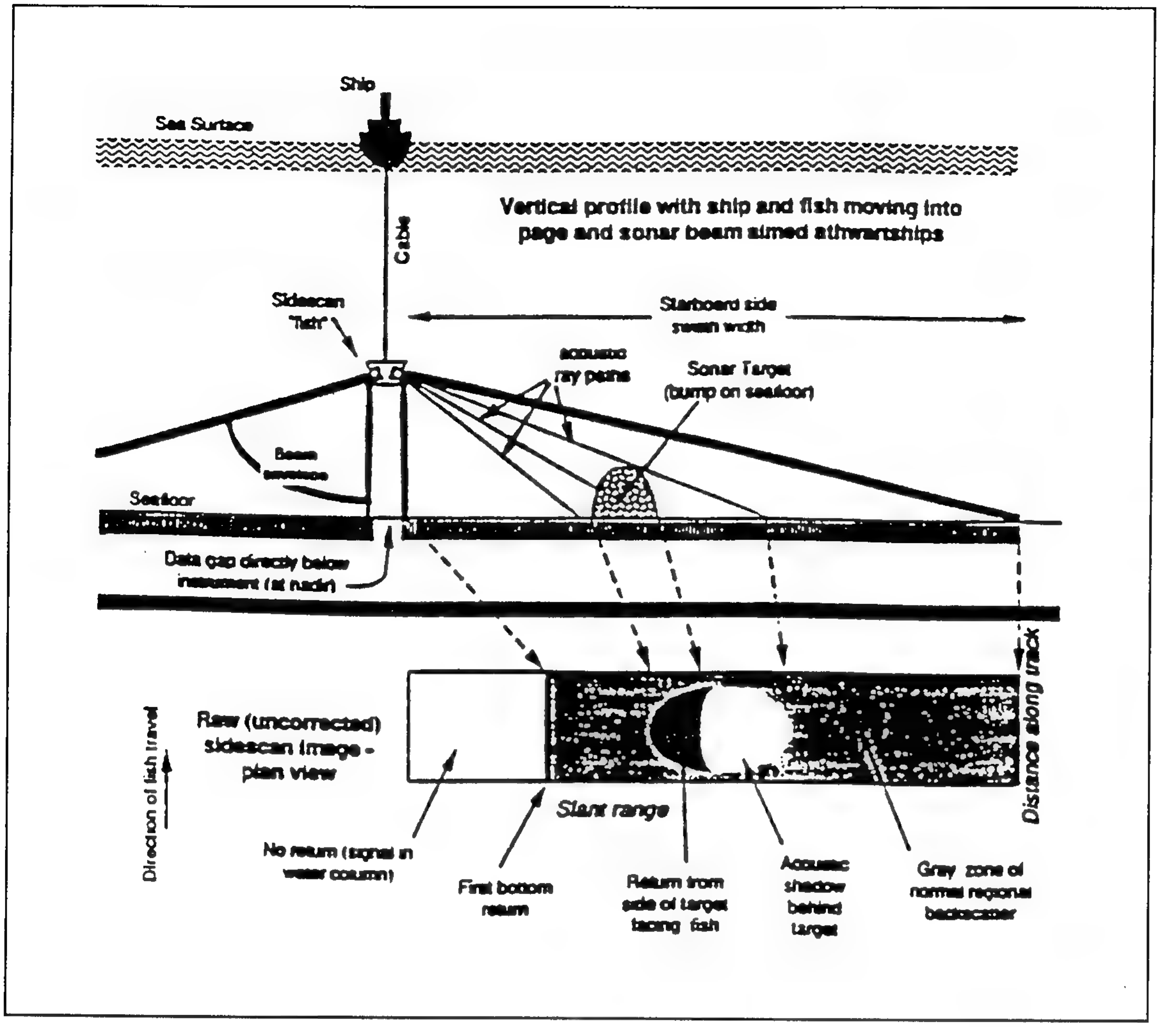


Figure 30. Configuration of acoustic side-scan sonar system (cross section) in water, showing relationship between acoustic signal, seafloor target, and raw side-scan image in plan view (from Ward 1993)

The maximum operating depth of side-scan sonar is typically about 6,000 m, while the tow speed should be between 0 and 2 knots. Resolution ranges from centimeters using the high-resolution/low-swath mode, to tens to thousands of meters in the wide-swath, low-resolution mode (see Table 9). In complex terrain, side-scan sonar imagery can become cluttered, especially where small objects are being examined, and visual inspection is often needed.

Two types of bathymetric mappers exist: profilers and swath mappers. Profilers such as the single-beam echo sounder collect data along a single line beneath the instrument. Swath mappers simultaneously produce multiple lines (tens to thousands) of parallel-track data. Swath mappers are subdivided into two types of technology used commonly: multibeam systems (e.g., Sea Beam) and split-beam side-scan. Multibeams electronically steer the transmission and receiver acoustic pattern to create an across-track, radiating set of a number of beams. Each beam's footprint on the seafloor constitutes the

horizontal resolution of the system. So far, all multibeam systems are hull-mounted, although deep and shallow-towed systems are under development.

Swath bathymetric mapping uses two types of split-beam side-scan sonar techniques: passive interferometry and phase sampling. Passive interferometry allows bathymetric mapping to be conducted and displayed in near real-time. Phase sampling requires a high-speed digital data link (e.g., fiber optic cable) and surface processor with special, multirow transducers for quadrature sampling of the received signals. The different types of acoustic side-scan sonar systems are summarized in Table 2.

Table 2
Summary of Characteristics of Five Different Acoustic Side-Scan Sonar Systems (from Ward 1993)

Systems	Type of Technology	Advantages	Limitations	Systems and Side-Scans
Multibeam	Focused beams (along track)	Along-track resolution and sampling; detection scale	Swath width and current depth rating	Klein MBFS CTECH MBSS
Split-Beam	Passive or phase-sampled	Swath bathymetry	Interface (demands high speed); only uses high frequency on DF systems	Jason® SEAMARC II, DSL-120, AMS-120
Single-Beam CHIRP	Frequency-modulated pulse	Swath width and sensitivity	Resolution in the high mode	AMS 36 SIS-7000 GLORIA MK II SAR
Single-Beam Continuous Wave	Dual frequency	High- and low-resolution modes and spectral imaging	Swath width (at high resolution)	EG&G 50/500 AMS 60/200 Klein 100/500 ARGO® FOSS ORION OE 6000
Rotated Beam Continuous Wave	Directed beams (across track)	Geometric corrections	Resolution (high mode)	DEEP TOW

Multiple focused beams (up to five) can be used to improve along-track resolution and detection compared with single-beam systems (e.g., Klein's MBFS). The use of a single-beam, dual-frequency system permits improvement of imaging for multispectral characterization in order to carry out both wide-swath mapping or search operations and higher resolution imaging (ORION, FOSS, Ocean Explorer 6000). The use of a chirp pulse enables higher range resolution and sensitivity compared with continuous wave systems at an equivalent frequency (GLORIA MKII, SAR, SIS-7000). Where steep slopes exist, a rotated beam side-scan system such as Deep Tow can rotate the beam direction allowing one beam to look upslope and the other to look downslope.

Data outputs

Data output consists of imaged sonographs, produced by translating acoustic backscatter signal into image pixels. Image processing and enhancement includes the capability for digitally overlaying a series of 2-D slices into 3-D bathymetric representations, enhancing selected parameters such as bottom roughness or contrast. Statistical assessment of bathymetric information includes analysis of slopes, relief, and other parameters.

Examples of sensor outputs

An example of an imaged side-scan sonar record is shown in Figure 21, an image of a 55-gal drum at an undersea disposal site, taken with 100-kHz side-scan sonar at a range of 100 m. Acoustic side-scan sonar is useful for rapid, large-scale mapping and bathymetry of underwater sites, including rocky hard-bottom and soft-bottom sediments. It can be used as an EPA Level I rapid reconnaissance and site selection tool to define major acoustic horizons and sediment types to a typical resolution of tens to thousands of meters. A more detailed survey of selected sites can follow using the acoustic sled (resolution of millimeter to centimeter), sediment profile imaging to achieve finer resolution down to 62 μm, or conventional ROV CCD imaging for rapidly scanning at near-photo quality resolution. An example of such a tiered use is a study by Menzie et al. (1982), who used acoustic side-scan sonar on the first day to rapidly map and define the area of interest, followed by sediment profile imaging the second day for finer scale mapping of sediment and biological activity at high resolution.

Costs to acquire, operate, maintain

Estimates of the cost of side-scan sonar systems are provided in the following chart based on vendor quotations and discussions. The Multibeam system is currently not available in a commercial deepwater version. Aside from purchase costs, an estimate is given for the needed product improvements. A Rotated Beam system may also require development depending on the system and frequency chosen. The cost of the Split-Beam system includes options added to a Dual-Frequency system but does not include any additional costs for fiber optic cable, faster computer, etc.

Side-Scan Sonar System	Development Cost	Purchase Cost	Total
Multibeam system	$250K	$250K	$500K
Dual-Frequency system	$0	$250K	$250K
Split-Beam system	$0	$250K + $100K	$350K
Rotated Beam	Unknown	Unknown	Unknown
CHIRP	Unknown	Unknown	Unknown

Technological maturity and risks

Maturity reflects the potential for changes in hardware and software design. The Split-Beam and Dual-Frequency systems are proven and technologically mature systems with reliable performance. The Multibeam system is a technologically young system although it has the potential for best performance due to its high detection and sampling rates.

Future development requirements

The Multibeam system requires significant development. The Rotated Beam system may require development depending on the system and/or frequency chosen.

RoxAnn System

Sensor name: RoxAnn System

Sensor category

In-water real-time survey/operational system for automatic seabed identification.

Description

The RoxAnn system consists of shipboard hardware and software that provides real-time automated classification of seabed roughness and hardness from conventional echo sounders (20 to 250 kHz) (Figure 31). Various combinations of roughness and hardness values are diagnostic for rock substrata and different textures of granular sediments. False color representations of bottom "type" are displayed in profile along a survey line. A 2-D map view of bottom type is then constructed from adjacent survey lines. This approach makes efficient use of traditional echo sounding equipment found on most vessels of opportunity. The software for signal logging, formulation, and display is written in Microsoft C, version 5.1 under the MICROPLOT label. A 386 computer with extended memory (2mb) enables over 4 million features to be stored. The on-screen display may consist of 64,000 track points, 2,000 coast points, 2,000 mapping line points, 1,000 data points, 3,000 way points, 700 buoys and events, and 50 moving targets (Chivers, Emerson, and Burns 1990).

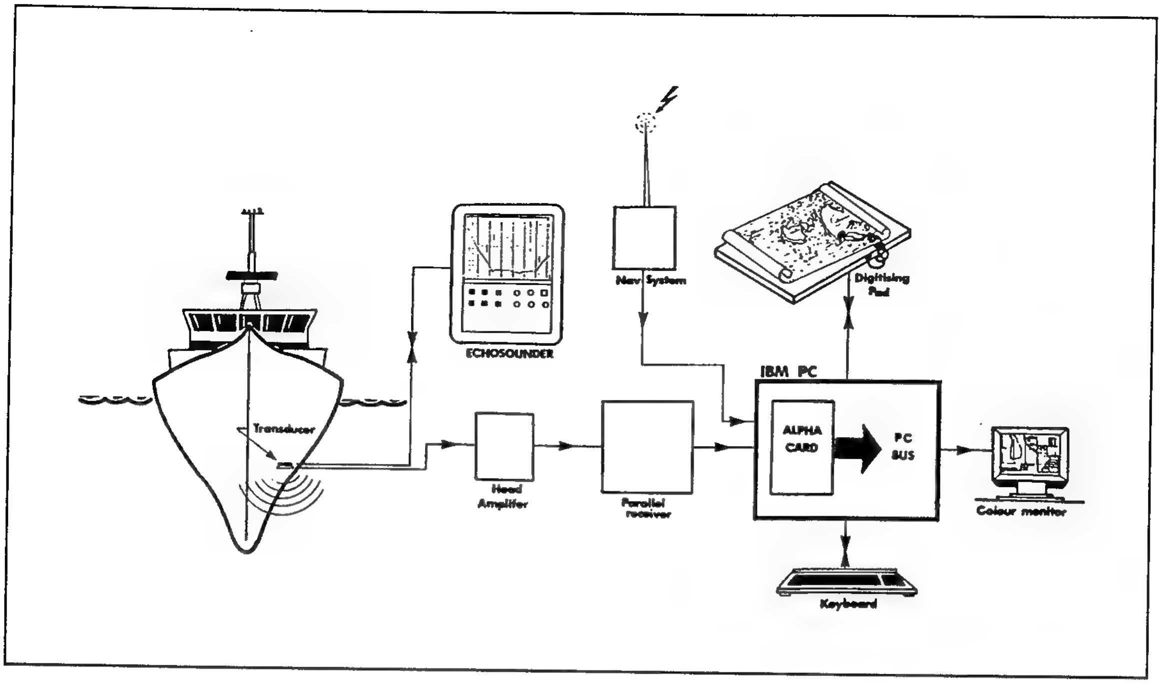


Figure 31. Schematic layout of the RoxAnn seabed discrimination system (from Chivers, Emerson, and Burns 1990)

Data outputs

An onboard signal processing system collects acoustic signals from conventional vessel echo sounders (Figure 31). Signal processing is applied to both the primary seabed echo (E1), and second echo reflected twice from the seabed and once from the sea surface (E2). The ultrasonic signal processor (USP) is used to extract E1 and E2 from the returning echo train. The value of E1 is the integral of that part of the first echo which arrives after removal of the initial normal backscatter and is a method of improving the signal to noise ratio (Chivers, Emerson, and Burns 1990). The E1 echo is used as an indicator of bottom roughness, and the E2 echo is a surrogate measure of bottom hardness. Estimates of bottom type are made by plotting the ratios of E1 (y-axis) against E2 (x-axis) in coordinant space (Figure 32). Values of various combinations of E1 and E2, as plotted in coordinant space, are assigned false colors for the purpose of map display (Figure 33). As with any remote sensing tool, a certain amount of ground truth verification is necessary to calibrate and correctly interpret the acoustic classifications.

Examples of sensor/system outputs

Figure 32 shows the empirical classification of seabed type defined by various combinations of E1 and E2. This bivariate plot is displayed as an inset on the overall survey EGA display (Figure 33).

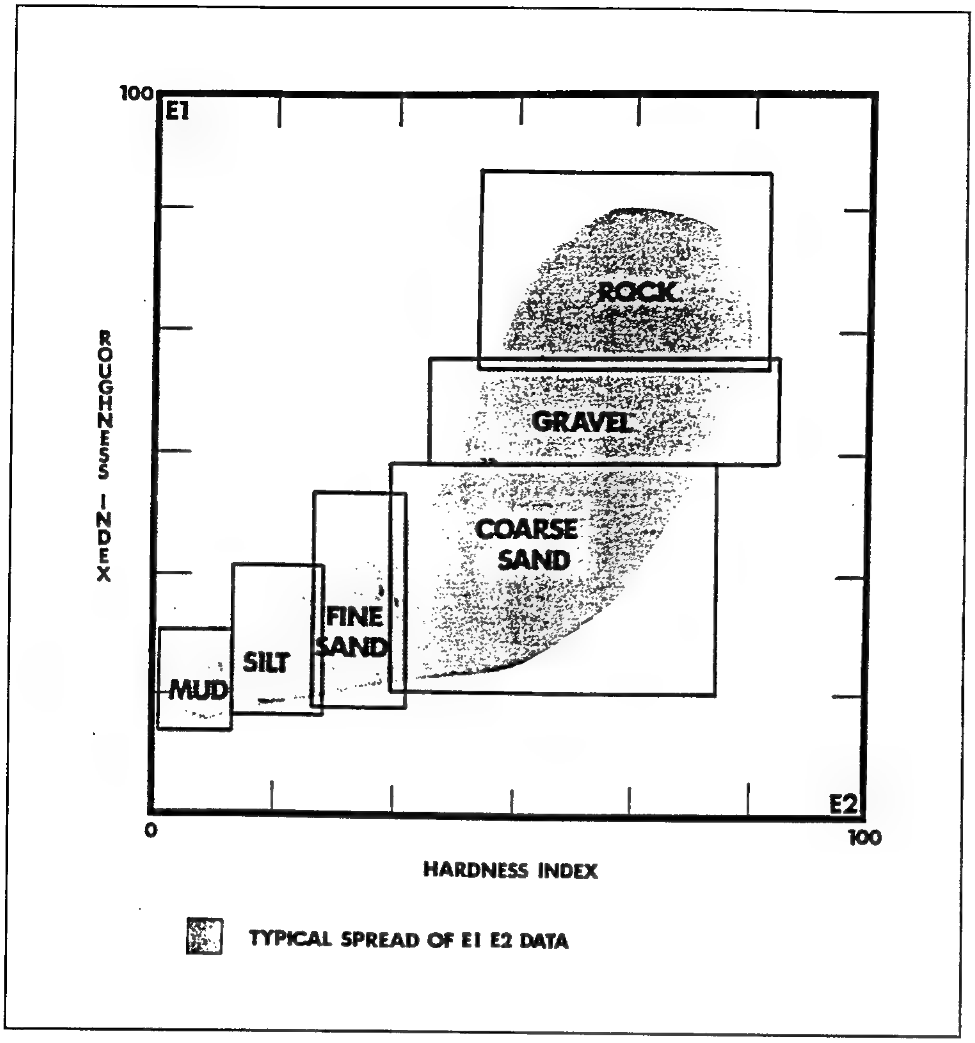


Figure 32. Empirical classification of bottom type from signal processed E1 and E2 data (from Chivers, Emerson, and Burns 1990)

Costs to acquire, operate, maintain

The cost for a turn-key system including installation is about $25,000 including all hardware and software. This cost does not include the acoustic transducer which is assumed to be available on a vessel of opportunity. Operational and maintenance costs are very low and comparable with any computer work station.

Technological maturity and risks

The maturity of this system is high. It is being used by commercial fishermen and for bottom surveying by government agencies and private industry

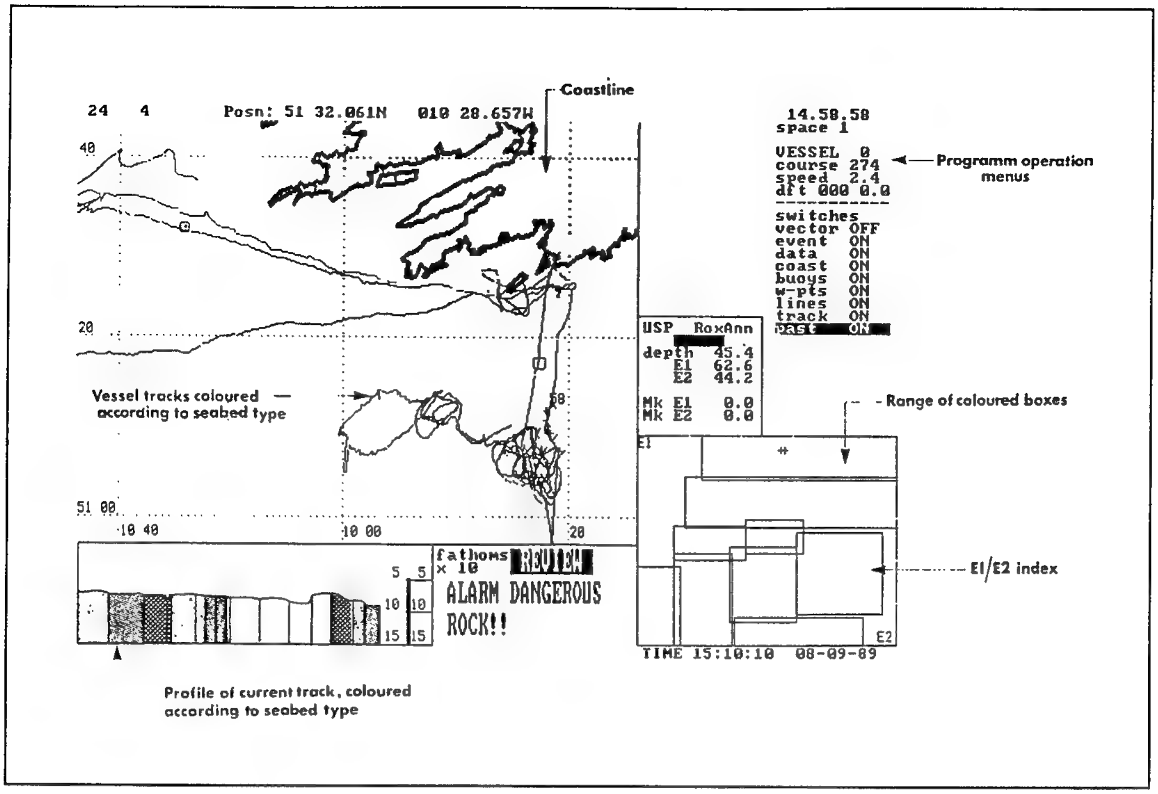


Figure 33. Full EGA display of the USP interfaced to MICROPLOT (from Chivers, Emerson, and Burns 1990)

and has proven itself in dredging projects, both in a survey mode and when providing real-time information to the dredger about bottom conditions in advance of the drag head.

Future development requirements

The system as currently configured for real-time display, and classification seems to fulfill most requirements. For repeated surveys, including data products from other sensors, it would be useful to input RoxAnn maps into a GIS system for the purpose of recall, overlay, and analysis with other mapped data.

Information sources

Hardware components of the system are marketed by Marine Microsystems, LTD., Capwell Works, Kinsale Road, Cork, Ireland; and the Microplot software package is provided by Sea Information Systems, Ltd., 42 Regent Quay, Aberdeen, Scotland.

4 Airborne Sensors

Hyperspectral Airborne Imaging

Sensor name: Compact high-resolution imaging spectrographic sensor (CHRISS)

Sensor category

Airborne hyperspectral system optimized for maritime applications.

Description

Hyperspectral imaging (HSI) is a technique for obtaining photometric images of ground terrain or aqueous surface at different spectral bandpasses (colors), i.e., at several different positions in the electromagnetic spectrum (Figure 34). If a few (say, 3 to 10) broad and noncontinguous channels are used, such as in the Landsat Thematic Mapper, the technique is called Multi-spectral Imaging (MSI). If tens to hundreds of narrow and contiguous channels are sensed, the technique is called HSI. Relatively crude Landsat imaging (7 spectral channels), with spatial resolution of 30 m, has been replaced by HSI from small aircraft with spatial resolution in the submeter range. Recent applications to aquatic environments in the spectral region where water transmits light allows extension of the technique to subtidal mapping problems.

The CHRISS system is a visible near infrared instrument which senses the spectral reflectance of all objects (pixels) in a scene using reflected sunlight. This system is flown on a light aircraft (e.g., twin engine Piper Aztec as shown in Figure 34). The design may be broken down into several major components including the following: (a) fore-optics that collect reflected light from the ground or submerged bottom in the range 425 to 950 nm, (b) variable optical slit and focal length that define the along-track spatial resolution, (c) cross-track ground sample distance and swath width, (d) an imaging spectrograph that supports over 440 resolution elements in the cross-track

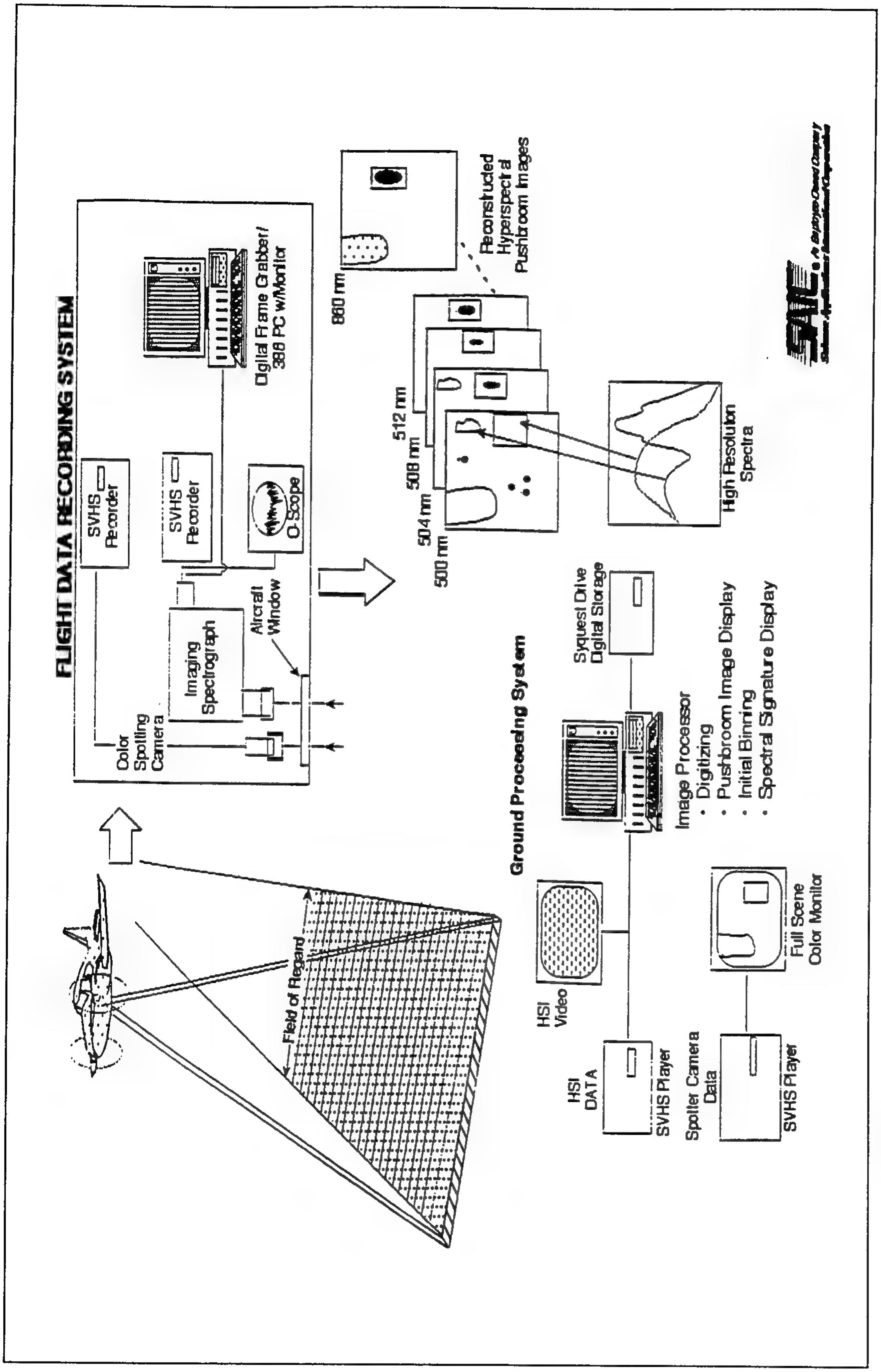


Figure 34. HSI of coastal environments using a small aircraft

dimension which is equivalent to 385, (e) 44-μm pixels on the CCD camera with a long pass filter placed over the CCD pixels to exclude wavelengths greater than 850 nm (second order false signals from the diffraction grating), (f) and a CCD focal plane sensor which is a 385 $\times$ 578 pixel array optimized for response from 420 to 950 nm. The full frame read-out rate is 35 frames per second (fps), but ongoing work is pushing the frame rate to 55 fps.

Data outputs

The basic HSI data set consists of an image cube (Figure 35). It is a set of images at many different spectral channels. All images are geo-registered using the Global Positioning System (GPS) so that they appear as a stack of images of the same scene. The image cube can also be thought of as a spectrum at each pixel of the image, where the number of points in the spectrum is equal to the number of spectral channels in the sensor. Reflectance spectra of objects of interest can be obtained by accessing the image brightness for a single pixel at every image plane. Individual image planes can be removed for traditional image processing.

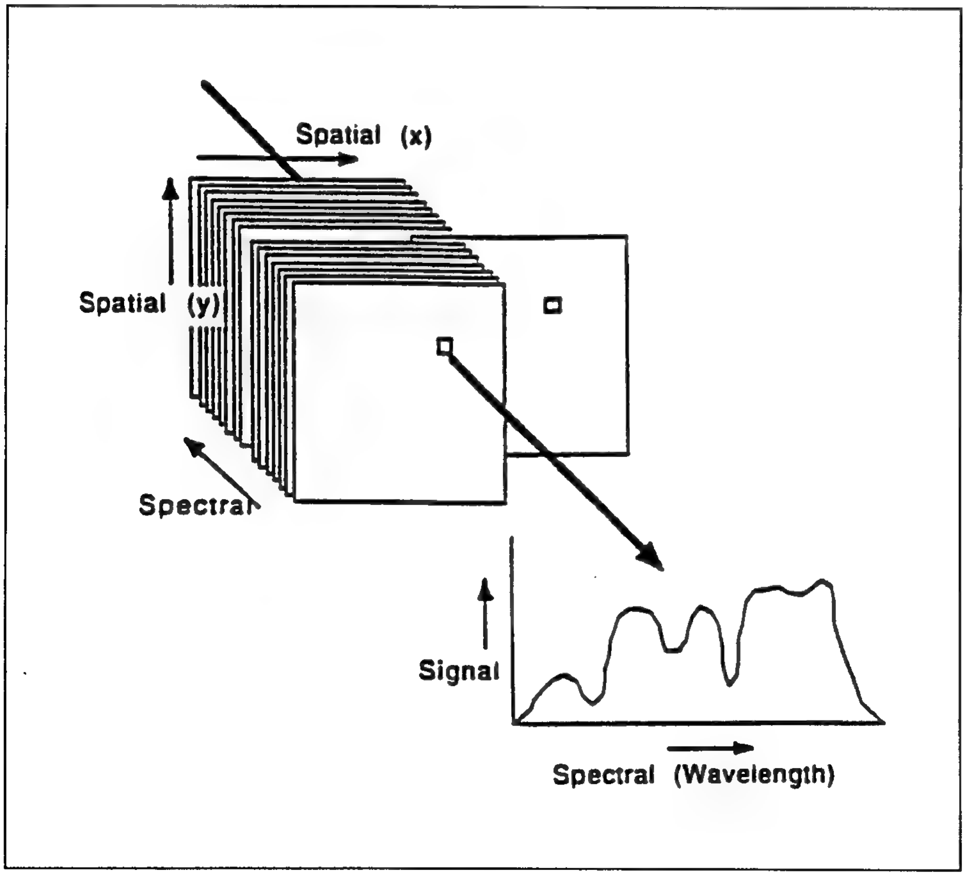


Figure 35. Data output from the HSI, consisting of image cube composed of stack of superimposed image planes of same scene

Examples of sensor output

A sample of data output is shown in Figure 36 for a version of this system that has been enhanced for marine applications (visible to near infrared or 433 to 832 nm). This image is taken from an altitude of 3,280 ft (984 m) along a region of coastline just west of the West Maui Sewage Treatment Plant in Hawaii. SETS Technology, Inc., has processed the image to enhance subsurface imagery. The image on the left is from the red portion of the visible spectrum near the chlorophyll minimum at 674 nm. This radiance is dominated by the surface reflection of the water, and so one does not see upwelling radiance from the bottom. The next image is that of a green channel at 530 nm with the red image on the left subtracted. The purpose of the subtraction routine is to help remove surface reflection. The next image is from the blue portion of the spectrum minus the red, again to remove the surface reflection. The image on the extreme right is the red, green, blue (RGB) color composite of the former three images. Note the clarity of the subsurface imagery as well as that of the sugar cane in the field at the bottom of the image. The coral in the fringing reef (lower left) appears slightly different from the rest of the coral (greener in the RGB image). Also, note leaching of the red soil into the surf zone near the beach.

An example of the preflight preparation software for HSI overflight is shown in Table 3. In this case, the flight altitude was 1 km, and aircraft speed was 90 knots. This model software permits calculation of the camera parameters before the flight and gives the rate of coverage and the signal-to-noise ratio desired for the survey.

Costs to acquire, operate, maintain

The system described here is a developmental prototype and is being optimized at this time for maritime applications. The cost for acquisition, including GPS registration, is estimated to be $250K. Special stabilization equipment is required for a helicopter flight platform.

Technological maturity and risks

This is a mature technology that has been used in commercial application for classified military projects and is being introduced into the environmental monitoring field for habitat assessment and change detection.

Future development requirements

Development is underway to optimize the system for marine application (e.g., Figure 36). The prototype system that produced this image is currently being flown and tested.

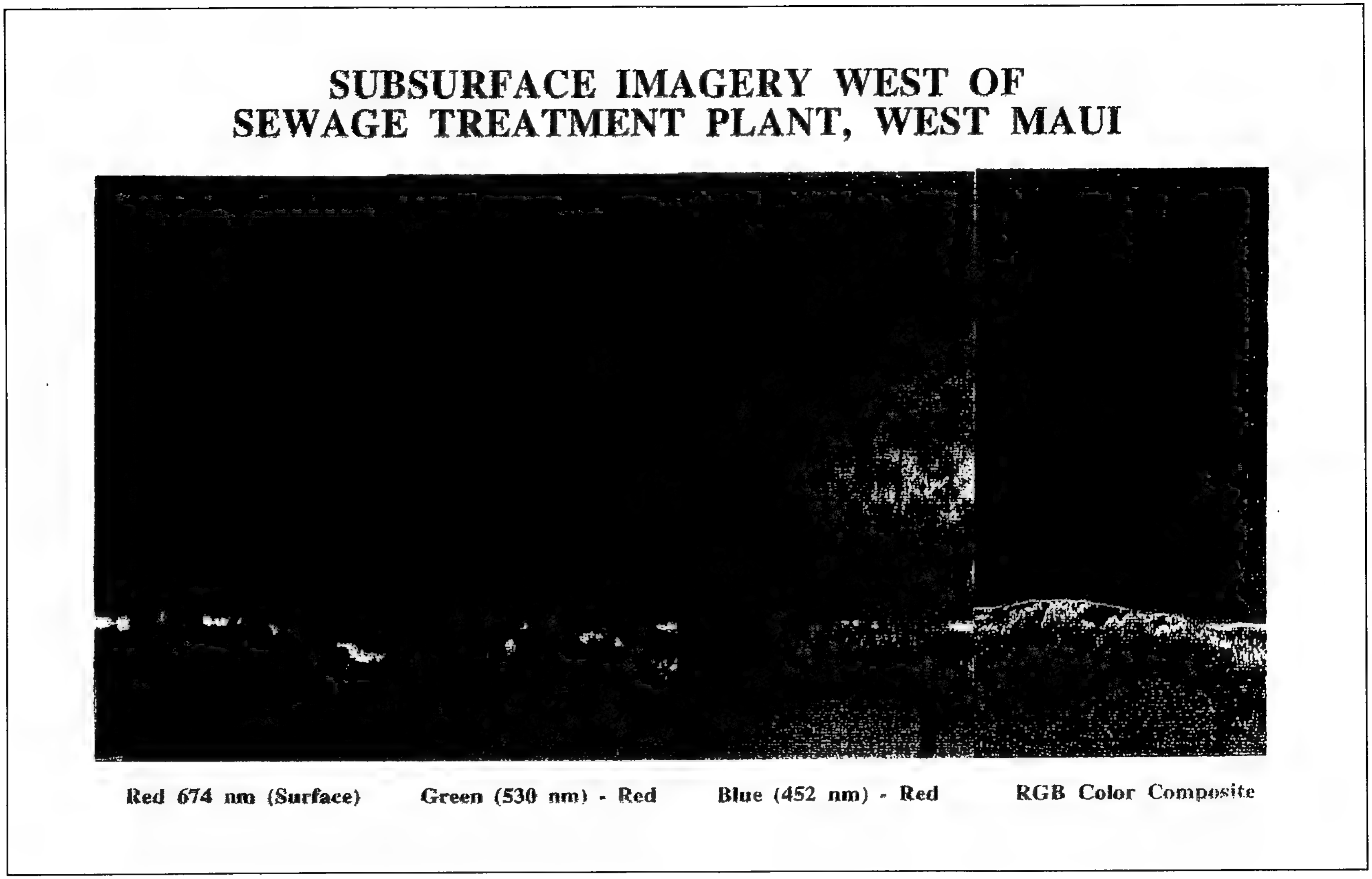


Figure 36. HSI of same coastal area west of sewage treatment plant, West Maui, Hawaii (from SETS Technology, Inc.)

Table 3
Sample HSI Analysis Model Output for the Venice Lagoon

H km	Optics d, mm	f/#	f, mm	#p, s	#p, l	s, μ	l, μ	slit μ	PSF μ	M	IFOV s, m	GSD s, m	RES l, m	IFOV l, m	GSD l, m	SW m	dis nm/mm	1 pix $\mu\lambda$ nm	res nm	λ low nm	λ high nm	opt bw nm	CCD int ms	SNR
Venice (Ground) 520 nm																								
1.0	3.5	4	14	290	385	44	44	85	40	1.0	6.07	6.00	2.86	3.14	3.14	1,210	56	2.46	5.24	440	1,151	9.8	127	1,764
Venice (Water) 520 nm																								
1.0	3.5	4	14	290	385	44	44	85	40	1.0	6.07	6.00	2.86	3.14	3.14	1,210	56	2.46	5.24	440	1,151	9.8	127	400
Camera Frame Rate												8 frames/sec												
Aircraft Speed												45 m/s = 90 kts												
Frame Transfer OH												6 ms												
Area Coverage Rate: 196 km^2/h																								

Note: "s" indicates in direction of flight and "l" is lateral to direction of flight. BINNING by 2 in lateral direction will increase GSD by X2 and increase SNR by 1.4. Ground albedo = 20 percent; water = JERLOV type IB (effective albedo of 4.44 percent).
Parameter Code Explanation: 520 nm = arbitrary spectral wave length; H = fly height; d = lens diameter; f/# = F stop; f = focal length; #p(s) = # of pixels (spectra) collected in forward flight; #p(l) = # of pixels (spectra) collected lateral to flight direction; s,l = pixel size (pitch) in two different directions (s, and l); slit = spectrometer slit size; PSF = point spread function (pixel distortion); M = magnification of spectrometer; IFOV (s) = instantaneous field of view in flight direction; GSD = ground sample distance; RES = instrument limited resolution; IFOV (l) = instantaneous field of view lateral to flight direction; SW = imaged swath width; dis = dispersion; 1 pix = pixel sampling distance; res = instrument resolution; λ low = lower spectral channel; λ high = upper spectral channel; opt bw = optical band width; CCD int = CCD camera read integration time; SNR = signal to noise ratio of pure water.

Information sources

Information about the SAIC Airborne Hyperspectral Program can be obtained from Steve Moran, Science Applications International Corporation, 4161 Campus Point Court, San Diego, CA 92121, (619) 458-5183. Hyperspectral data analysis for marine applications is performed jointly by SAIC and SETS Technology, 300 Kahelu Avenue, Mililani, HI 96789. The technical contact is Dr. Gregory Mooradian, (808) 625-5262.

Light Detection and Ranging (LIDAR)

Sensor name: Airborne LIDAR (Light detection and ranging)

Sensor category

Airborne remote sensing of water properties and bathymetry.

Description

Quantitative LIDAR measurements of atmospheric and ocean parameters have evolved from 1970's applications with technology improvements for remote sensing and mapping. Recent advances include airborne, laser-based depth sounding and environmental sensors for measuring subsea parameters. Four basic types of LIDAR environmental measurements are used: (a) backscatter, (b) DIAL (DIfferential Absorption LIDAR), (c) Raman, and (d) Doppler velocity. Typical LIDAR ocean property measures focus on bathymetric and water properties using active system techniques to measure attenuation, scatter, reflectivity, and then deriving absorption and albedo (whiteness) parameters. Absorption techniques (Raman and DIAL) show promise for mapping ocean chemicals but are generally developmental at this time.

LIDAR systems consist of three major elements: (a) the transmitter, (b) the receiver/scanner, and (c) the data acquisition and control system. An operational airborne LIDAR survey system is represented by the Australian LADS (Laser Airborne Depth System) in Figure 37. The COE and Canadian Department of Science SHOALS (Scanning Hydrographic Airborne LIDAR Survey) on a helicopter uses similar technology. LADS uses laser transmitting, receiving, and scanning components mounted on a stabilized platform. A pulsed ND:YAG laser outputs an infrared (IR) wavelength of 1,064 nm that is frequency doubled to a 532-nm green pulse. The IR beam is directed down and provides the initial time, height, and surface reference while the green pulse is scanned in a swath across the flight track. Each green pulse is backscattered from the surface and directed to the receiving optics. The remaining energy at the water's surface propagates through the water column and reflects

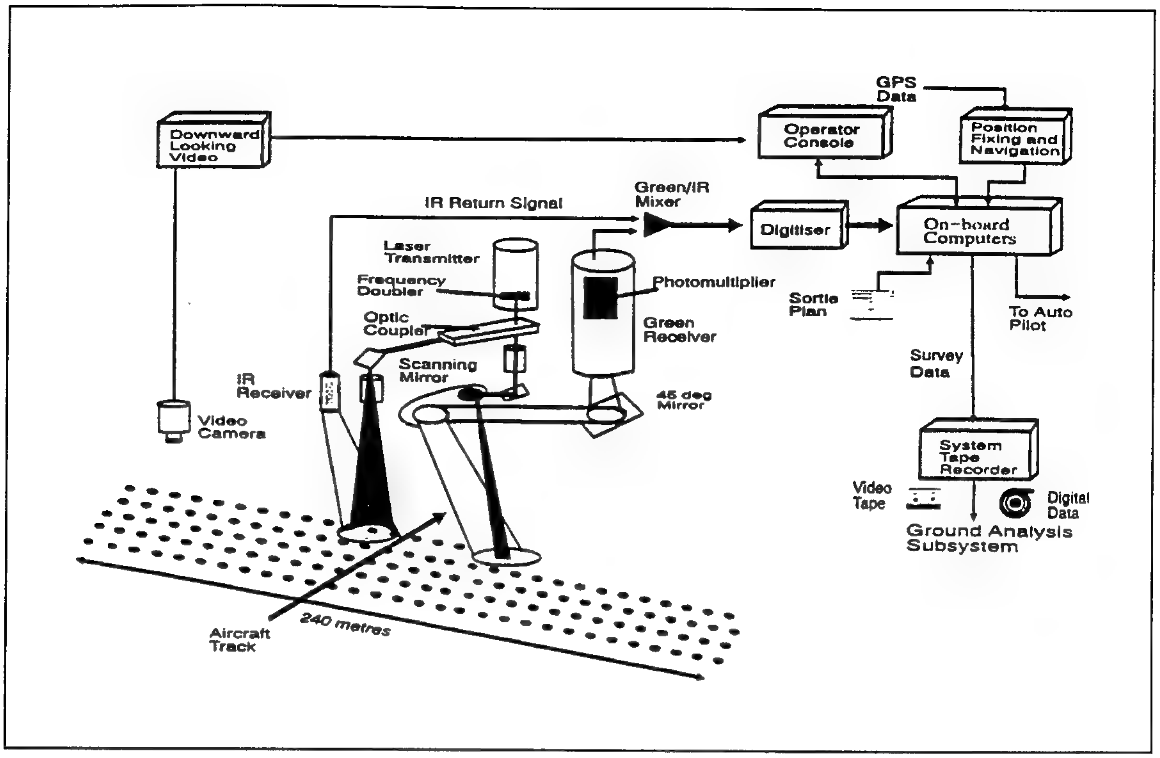


Figure 37. LADS system diagram

off the sea bottom back to the airborne detector. The time difference between the surface return and bottom return correspond to water depth.

Generally, LIDAR system performance is dependent on the following major factors: laser power, height, sea surface determination, and water clarity. Depth accuracy of 50 $\pm$ 0.3 m can be attained. SHOALS uses five receiver channels, three surface channels (infrared, Raman, and green wavelengths), and two bottom channels (both green wavelengths). Use of multispectral scanners with LIDAR can characterize a variety of water bottom morphologies in coastal environment assessments.

LIDAR has been used in a field experiment in Hawaii to obtain spectral emission data from coral reefs.[1] The LIDAR laser pulse periodically samples a spot a few tens of centimeters in diameter as the aircraft flies along the reef crest. The purpose of this experiment is to see if the spectral return can be interpreted in terms of physiological health of corals.

LIDAR technology provides advantages in remote assessment of transport properties in ways that in situ monitors cannot. Capabilities include broad 3-D spatial coverage, high spatial and temporal resolution, true in situ measures, and real-time results. Laser-based sensors are designed to take

[1] Personal Communication, June 1995, John Hardy, Huxley College of Environmental Studies, Bellingham, WA.

advantage of the unique properties of a laser source to mitigate the absorption and scattering effects of water. Figure 38 and Table 4 summarize demonstrated LIDAR capability and utility.

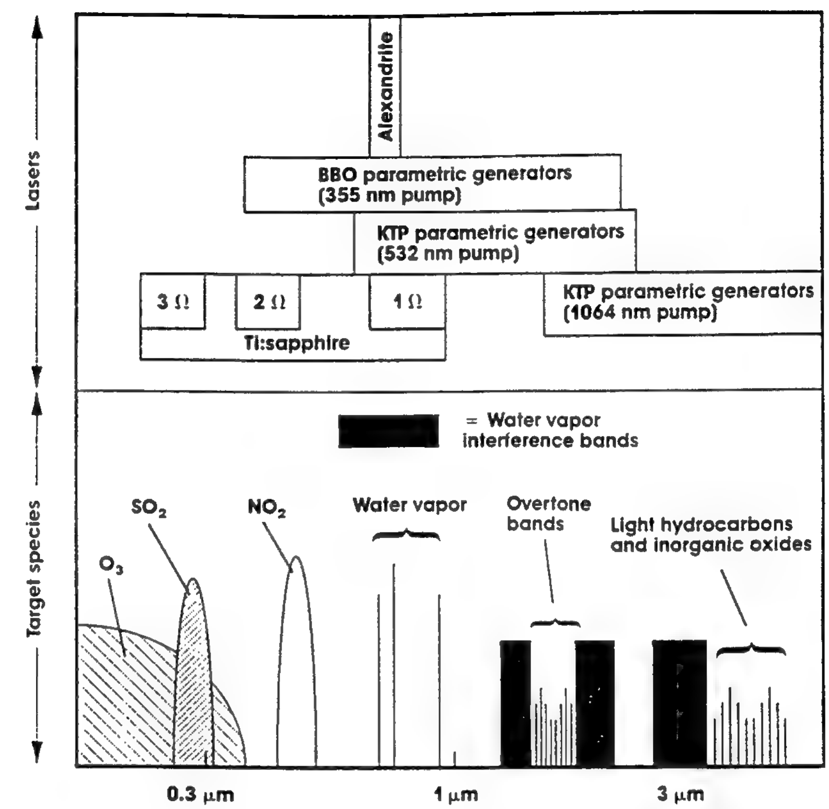


Figure 38. Spectral and species coverage of current solid-state laser technology (from Moody, Cunningham, and Pence 1993)

Table 4
Types of LIDAR Measurements

Type	Description	Application
Backscatter	1-3 fixed wavelengths	Density, size, range; amplitude or phase detection
DIAL	2 wavelengths (tunable) around specific molecular absorption feature	Species specific chemical mapping
Raman	Fixed or tuneable laser, high-resolution detector	Like DIAL, different target species and interferences
Doppler Velocity	Narrowband/SLM laser, detected frequency shift	Remote current measurement

Data outputs

Data outputs consist of high-resolution analog video or digital image data containing specific wave forms for each pixel. Wave-form analysis yields depth representations using color or grey scales, echo classifications, and other relevant data associated with each shot.

Examples of sensor/system outputs

Figure 39 shows data from a Swedish helicopter borne LIDAR called FLASH (FOA Laser Airborne Sounder for Hydrography). The upper left shows real-time swath with color coded depths, the right shows enlargements for detailed investigation, and below shows specific wave forms of selected pixels. Detected depth and bottom contrast are affected by the LIDAR FOV (Field Of View) which is especially important in irregular bottoms. Estimates of water turbidity, attenuation, and other parameters can also be determined. A HOSS (Hydro Optical Sensor System) that also operates from the helicopter provides water profile measures shown in Figure 40 and measures daylight attenuation (K), beam attenuation (c), signal scatter (s) and backscatter (B).

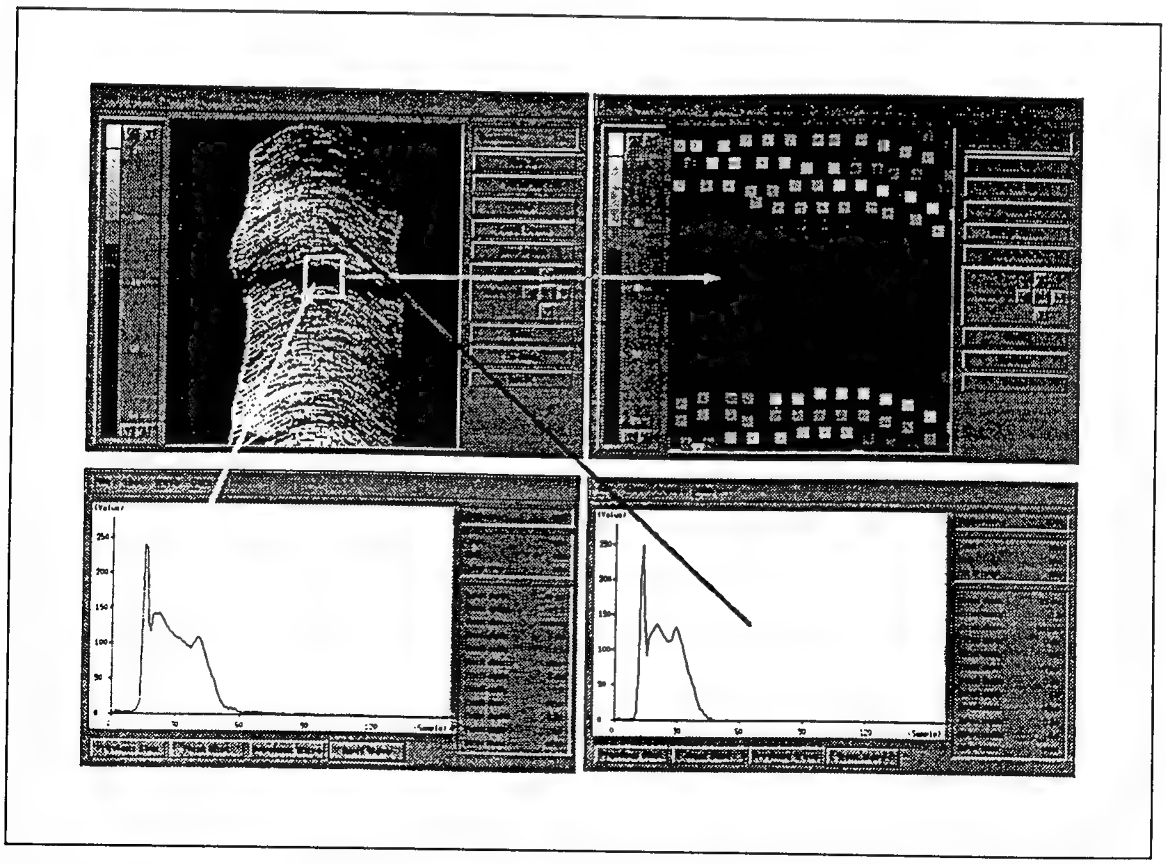


Figure 39. FLASH data. (a) upper left, real-time swath with color coded depths; (b) upper right, enlargement for detailed investigation; and (c) lower left and right, specific wave forms of selected pixels (from Koppari, Karlsson, and Steinval 1994)

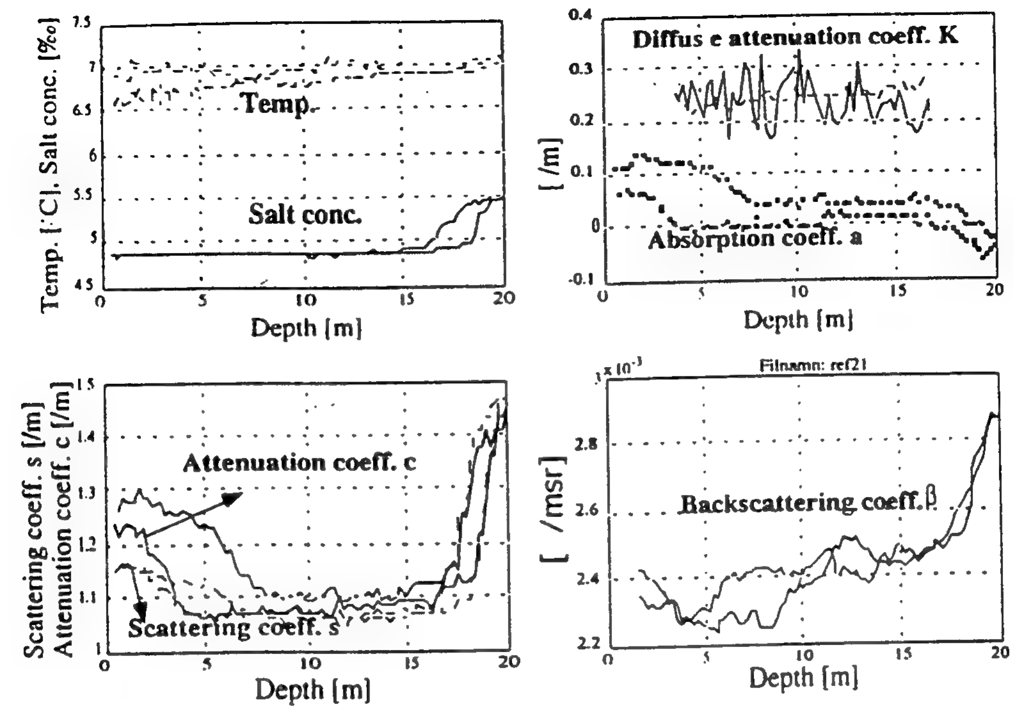


Figure 40. HOSS profiles (from Koppari, Karlsson, and Steinval 1994)

Figure 41 shows a comparison of acoustic and FLASH laser depth soundings. An example of a 3-D Digital Terrain Map (DTM) surface which SHOALS can produce is presented in Figure 42.

Wave-form and multispectral analyses provide the capability to detect and classify chemicals of interest using established analytic chemistry methods. Spectroscopic measures may include fluoroscopic, colorimetry, and other analytical techniques. Research and development in related analysis are ongoing to apply these techniques for detailed field screening protocols and quality standards. Field spectroscopic instrumentation and methods are a rapidly improving and growing analytical area that can greatly improve environmental analytical capability.

Costs to acquire, operate, maintain

In general, LIDAR equipment costs are dropping, and current system acquisition costs are in the $100K range for fixed frequency or DIAL system hardware. Development of small, portable systems and software for data analysis are continuing. System development costs for an airborne package are application specific. Operational costs are not available but are expected

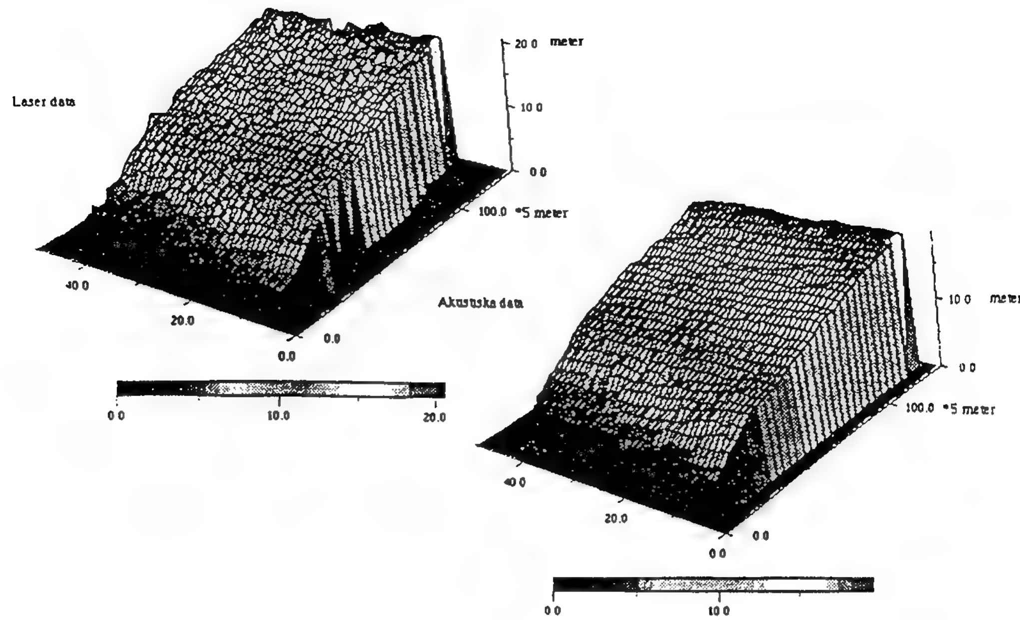


Figure 41. Laser versus acoustic depths (from Koppari, Karlsson, and Steinval 1994)

to be significantly lower than conventional acoustic surveys because of rapid survey rates (to 50 km²/hr), processing rates (approaching 1:1 for bathymetry) and high effectiveness (data yields to 95 percent).

Technological maturity and risks

Ocean applications for airborne LIDAR, both realized and potential, are widespread in defense and commercial areas. Operational systems for bathymetric surveying have recently become available including LADS (in service 1993), FLASH/Hawk Eye (field trials 1989-92), SHOALS (field trials 1994-95), U.S. Navy's Ocean Water LIDAR (field trials 1989-94), and Terra Survey's LARSEN LIDAR (operating since 1985). Developmental systems for mapping chemicals (e.g., fuel spills) have been tested by the U.S. Coast Guard and Canada and have successfully demonstrated detection and classification utility. The use of LIDAR spectra for interpreting coral status and health is in an early experimental stage.

From a systems perspective, LIDAR components are becoming more compact and rugged. Airborne LIDAR components are maturing from developmental applications to a second generation technology focused on needs of the user whose concern is the data, not the technique. The technology and hardware are adapting to meet the needs of commercial users and to lower the costs of components. Recent emphasis on DIAL systems working in spectral

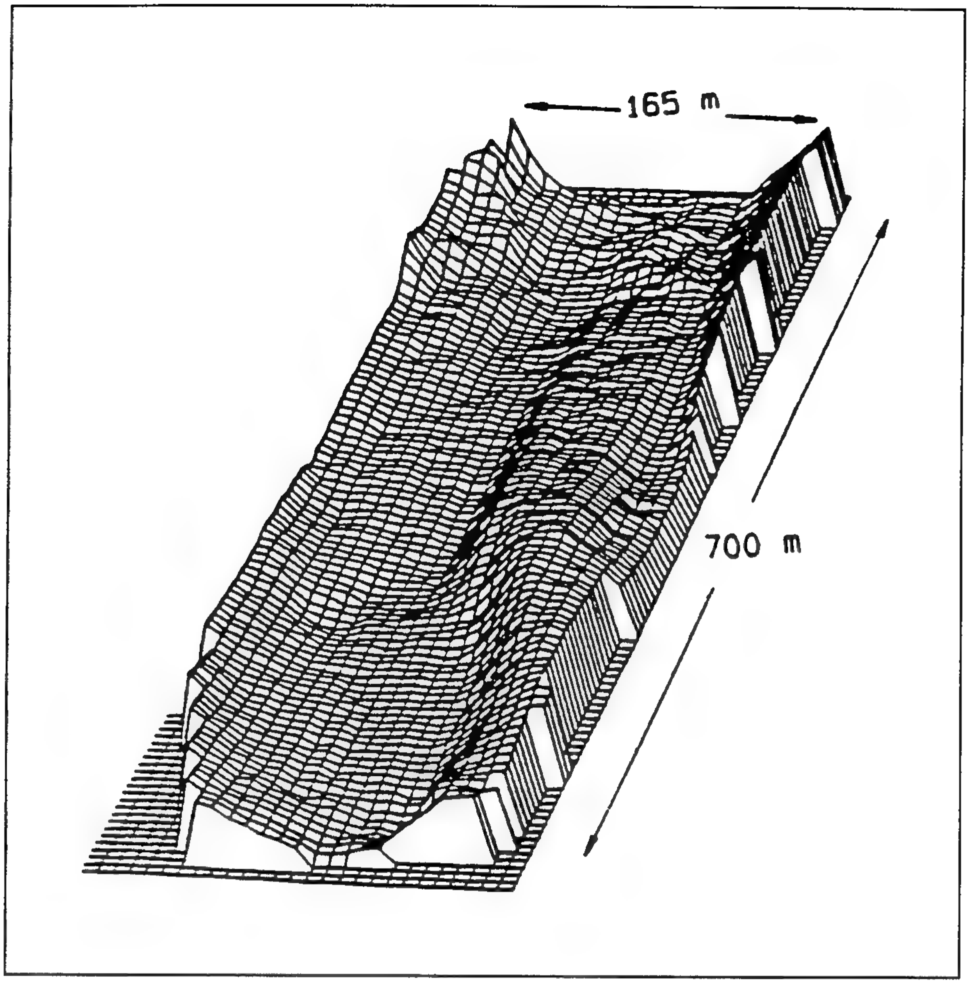


Figure 42. SHOALS 3-D surface DTM (from Lillykrop et al. 1994)

regions that allow chemical detection and mapping of environmental parameters is proceeding by various commercial and industrial firms. Technology risk is moderate and becoming lower because of growing test and operational experience of developed airborne LIDAR systems.

Future developments

This technology has potential for characterizing shallow-water aquatic vegetation and coral reefs. Accuracy and sensitivity of LIDAR systems are evolving, and work continues to improve system performance and survey effectiveness (i.e., coverage, survey rates). Recent improvements in laser transmitter and detector/scanner technology continue to increase the price-performance points for marine life surveys and monitoring applications. Recently, laser and receiver gating techniques (e.g., Q-switched) have improved water penetration depths for surveys and surveillance and can provide time-resolved fluorescence measurement for chemical deconvolution. Laser-gated DIAL systems are being developed and tested for use in pollutant

or spill detection and localization. Future emphasis will be focused on data analysis software and instrumentation refinements to improve analysis of LIDAR measures.

Certification and operational use of airborne LIDAR for hydrographic and marine (life) surveying is on a rapid track by international and national firms and governments. Many new applications are envisioned and under development in environmental characterization, assessment, monitoring, and pollution detection.

Information sources

Coral Health: John T. (Jack) Hardy serves as Director of the Center for Environmental Sciences, Huxley College of Environmental Studies, Bellingham, WA 98225-9079, (206) 650-6108.

Summary and Conclusions

The on-bottom, in-water, and airborne sensors described in this review can provide a wide range of environmental data over vastly different spatial scales with different degrees of resolution or discrimination.

The range of depth penetration into sediments for all acoustic systems, including the ones reviewed here, are compared in Table 5. All of the sensors reviewed here are rated for their performance in sensing soft bottom, hard bottom, and fisheries (Tables 6 to 8). The different sensors are compared for resolution, speed, spatial coverage, ability to carry out sensing in situ, and ability to deliver data in real time (Table 9). In terms of the COE's surveying and monitoring requirements, no single sensor has sufficient dynamic range or spatial scale to meet all COE requirements. However, combinations of sensors can go far in meeting specifications. The most efficient use of these tools is to carefully define the questions necessary to address a particular problem, followed by an assessment of the time/space scales required to answer these questions. This important initial excercise will ensure that the sensors are appropriately chosen to address the dynamics operating in both space and time at a site of interest. Once the time and space scales are defined, the population of sensors can be narrowed down to a subset appropriate for a particular application. For example, the COE may be focused on a particular disposal operation (a scale covering a few thousand square meters), but be interested in both larger scale effects, within a few square kilometers around the site, and smaller scale effects within the disposal site (grain-size changes, faunal colonization over time, or fish distribution patterns).

The above sample problem is typical and requires a tiered survey protocol with large-scale, low-spatial resolution sensors being used first (and perhaps only once), followed by higher resolution sensors deployed over several times

Table 5
Comparison of Depth Penetration Into Sediments for All Acoustic Sensors, Including Those Reviewed

Frequency Hz	Vertical Resolution, m	Depth of Penetration Into Bottom (using 2 cycles/pulse)	Applications	Sensor
10	150	Kilometers	Hard bottom (rocks); consolidated sediments; water	Seismic
100	15	10's to 100's of meters	Hard bottom (rocks); consolidated sediments; water	Seismic
1,000	1.5	Centimeters to 10's of meters	Hard bottom (rocks); consolidated sediments; water	Acoustic side-scan sonar (kHz range)
100,000	0.015	1's to 100's of centimeters	Soft-bottom sediments; benthic organisms; water column plume tracking	ASI
1,000,000 (ultrasound)	0.0015	1's - 10's of centimeters	Soft-bottom sediments; benthic organisms; water column plume tracking	Acoustic MHz Sled

to acquire data on site dynamics at smaller scales. For example, the first tier is applied to mapping first-order features such as major sedimentary and/or hard ground features, distribution of sea grass and algal beds, migrating fish aggregations, or the approximate dimensions of a dredged material mound. These features can be characterized by kHz acoustic side-scan or imaging/measuring airborne sensors. Second-order features, such as the physical and chemical dredged material footprint, identification of the species of migrating fish, species of algae and sea grass, or mapping of assemblages of epifaunal benthos, are appropriately mapped using laser line scan, gamma sled, CS^3 sled, sediment-profile imaging, or MHz acoustic imaging. Finally, third-order features, such as sediment grain-size, sediment chemistry, spatial tiering of infauna, and imaging of buried dredged material fabrics, can be sensed using sediment profile imaging, UV fluorescence profile imaging, or ultrasound imaging.

The degree of sensor tiering actually employed in a project will depend on the questions being asked, dimensions of interest, and cost benefits of remote sensing relative to traditional methods of data acquisition. Documented examples of using a tiered combination of remote sensing tools are side-scan followed by sediment profile imaging (Menzie et al. 1982) and gamma sled followed by sediment profile imaging (Rhoads 1990), or helicopter mapping followed by sediment profile imaging, and later by traditional benthic sampling (Anselmetti et al. 1993).

Table 6
Capabilities of On-Bottom/In-Bottom Sensors for Sensing of Soft- and Hard-Bottom Sediments and Fisheries Resources

Parameter	Sediment Profiling Camera	REMOTS® Hyper-spectral UV Imaging Camera	MHz Acoustic Sled	Acoustic Sub-Seabed Inter-rogator (ASI)
Bathymetry	No	No	No	No
Hard bottom	No	No	Yes, boulders + fines (Exp)	Yes, boulders + fines (Exp/Dev)
Soft bottom	Yes	Yes (Exp/Dev)	Yes (Exp)	Yes (Exp/Dev)
Sediment stratigraphy, layers	Yes	Yes (Exp/Dev)	Yes (Exp)	Yes (Exp/Dev)
Nature of sediment-water interface	Yes	Yes (Exp/Dev)	Yes (Exp)	Yes (Exp/Dev)
Depth profiles (sediment)	Yes	Yes (Exp/Dev)	Yes (Exp)	Yes (Exp/Dev)
Sediment grain size	Yes	Yes (Exp/Dev)	Yes (Exp)	Yes (Exp/Dev)
Percent water, porosity	No	No	Yes (Exp/Dev)	Yes (Exp/Dev)
Lithology	Limited	Limited (Exp/Dev)	Limited (Exp-/Dev)	Limited (Exp/Dev)
Elemental composition	No	No	No	No
Contaminants	No	Yes (Exp/Dev)	No	No
Erosion, resuspension, sedimentological processes	Yes	Yes (Exp/Dev)	Yes (Exp)	Yes (Exp/Dev)
Chemical processes	Limited	Yes (Exp/Dev)	No	No
Biological processes	Yes	Yes (Exp/Dev)	Yes (Exp)	Yes (Exp/Dev)
Fish (presence, biomass)	No	No	Yes (Exp)	Yes (Exp/Dev)
Benthic epi- and infauna	Yes	Yes (Exp/Dev)	Yes (Exp)	Yes (Exp/Dev)
Submerged aquatic vegetation (SAV)	Limited	Limited (Exp/Dev)	Yes (Exp)	Yes (Exp/Dev)
Turbidity	Limited	Limited (Exp/Dev)	Yes (Exp)	Yes (Exp)

Note: Yes = Measures this parameter, in routine use; Exp = Measures this parameter, in experimental stage; Dev = Measures this parameter, in development stage; Demo = Measures this parameter, advanced to demonstration stage; Limited = Measures this parameter, but results only qualitative or semiquantitative; Indirectly = Parameter measurement may be estimated; No = Cannot measure this parameter.

Table 7
Capabilities of In-Water/Near-Bottom Sensors for Remote Sensing of Soft- and Hard-Bottom Sediments and Fisheries Resources

Parameter	Laser Line Scan System (LLS)	Gamma Sled	Continuous Sediment Sampling System (CS^3 Sled)	Acoustic Side-Scan Sonar	RoxAnn
Bathymetry	Yes	Yes	Yes	Yes	Yes
Hard bottom	Yes (Demo)	Yes	No	Yes	Yes
Soft bottom	Yes (Demo)	Yes	Yes	Yes	Yes
Sediment stratigraphy, layers	No	No	No	No	No
Nature of sediment-water interface	Yes (Demo)	Limited	Limited	Yes	Yes
Depth profiles (sediment)	No	No	No	No	No
Sediment grain size	Limited (mm or cm)	No	Limited	No	Textures
Percent water, porosity	No	No	Yes	No	No
Lithology	Yes (Concept)	Yes	Yes	Indirectly	No
Elemental composition	Yes (Concept)	Limited	Yes	No	No
Contaminants	Yes (Concept)	Yes (inorganic)	Yes (metals, elements)	No (unless large objects)	No
Erosion, resuspension, sedimentological processes	Yes (Demo)	Yes	Limited or Indirectly	Yes	Indirectly
Chemical processes	Yes (Concept)	Yes	Yes	Limited or Indirectly	No
Biological processes	Yes (Demo)	Limited, Indirectly or No	Limited, Indirectly or No	Yes	No
Fish (presence, biomass)	Unknown	No	No	Yes	No
Benthic epi- and infauna	Yes (Demo)	No	No	Yes	Yes
Submerged aquatic vegetation (SAV)	Yes (Demo)	No	No	No	Yes
Turbidity	Interferes	No	No	No	No

Note: Yes = Measures this parameter, in routine use; Exp = Measures this parameter, in experimental stage; Dev = Measures this parameter, in development stage; Demo = Measures this parameter, advanced to demonstration stage; Limited = Measures this parameter, but results only qualitative or semiquantitative; Indirectly = Parameter measurement may be estimated; No = Cannot measure this parameter.

Table 8
Capabilities of Airborne Sensors for Remote Sensing of Soft- and Hard-Bottom Sediments and Fisheries Resources

Parameter	Hyperspectral Imaging, HSI	LIDAR
Bathymetry	Yes	Yes
Hard bottom	Yes	Yes
Soft bottom	Yes	Yes
Sediment stratigraphy, layers	No	No
Nature of sediment-water interface	Possibly	Possibly
Depth profiles (sediment)	No	No
Sediment grain size	No	No
Percent water, porosity	No	No
Lithology	Possibly	No
Elemental composition	Yes	No
Contaminants	Possibly	Oil?
Erosion, resuspension, sedimentological processes	Yes	Yes
Chemical processes	Yes	Oil?
Biological processes	Yes	Yes
Fish (presence, biomass)	No	No
Benthic epi- and infauna	Yes	Yes
Submerged aquatic vegetation (SAV)	Yes	Yes
Turbidity	Yes	Yes

Note: Yes = Measures this parameter, in routine use; Exp = Measures this parameter, in experimental stage; Dev = Measures this parameter, in development stage; Demo = Measures this parameter, advanced to demonstration stage; Limited = Measures this parameter, but results only qualitative or semiquantitative; Indirectly = Parameter measurement may be estimated; No = Cannot measure this parameter.

Most of the sensors described in this review represent significant capital costs, and several of these sensors are still in developmental stages and not commercially available. A reasonable range of costs for sensor acquisition is from $50K to several $100K. In addition, recurring costs associated with maintaining in-house expertise have to be considered. The data products from most of these sensors require skill in data reduction, data processing, as well as data interpretation. The suitability of these sensors for routine environmental/resource information must therefore be balanced with capital and maintainance costs, as well as recurring costs of maintaining a trained staff to provide expertise in both field deployment and interpretation of data products.

Table 9
Comparison of Different Sensors

Sensor	Rate of Sensing and Analysis	Minimum Spatial Resolution
Sediment-Profile Camera	3 replicates/5 min; slides possible in 1 hr	μm to mm
REMOTS® UV Imaging System	3 replicates/5 min; images in 45 sec to several min	RGB imaging: 100's of μm UV imaging: 400 μm
MHz Acoustic Sled	Data in seconds to minutes	mm to cm
Acoustic Subseabed Interrogator (ASI)	Data in seconds to minutes	mm to cm
Laser Line Scan System (LLS)	346,000 m^2/hr in clear water; data in seconds to minutes	mm to cm
Gamma Sled	Data can be viewed in 60-sec intervals; 1 spectrum produced in 30-60 min; 2-D and 3-D maps produced in 24-hr cycles	1/1200 nm
Continuous Sediment Sampling System (CS^3)	Elemental analysis (XRF) takes up to 20 hr after sample arrives in lab	cm
Acoustic Side-Scan Sonar	Seconds to minutes	≥ 1 m
RoxAnn	Seconds to minutes	μm (mud size roughness)
Hyperspectral Imaging (HSI)	Seconds to minutes	Depends on flight altitude
LIDAR (4 types)	Seconds to minutes	Depends on flight altitude

Sensor	Operational Water Depth, m	Maximum Vessel Speed Permissible, knots	Footprint Area of 1 Sampling Event	Altitude (above seabed or sea surface)
Sediment-Profile Camera	0 - 4,000 m	Depth-dependent: no drift permissible at shallow depths, some drift at greater depths	Vertical section of 15 × 20 cm	± 20 cm at sediment-water interface
REMOTS® UV Imaging System	100 m	Same as above	Same as above	Same as above
MHz Acoustic Sled	Experimental so far	Experimental so far	2-cm-diam circle	8 cm above sediment (experimental version)
Acoustic Subseabed Interrogator (ASI)	Experimental so far	Experimental so far	Ca. 5-m-diam circle	45 cm

(Continued)

Table 9 (Concluded)				
Sensor	**Operational Water Depth, m**	**Maximum Vessel Speed Permissible, knots**	**Footprint Area of 1 Sampling Event**	**Altitude (above seabed or sea surface**
Laser Line Scan (LLS)	Cable limits use to 690 m; LLS rated to 1,800 m.	6	70° horizontal swath width (ca. 45-63 m)	2.4-39 m above seabed
Gamma Sled	100 m, or more if needed	3 - 4	20 cm footprint	Just above or on seabed
Continuous Sediment Sampling System (CS^3)	100 m, or more if needed	3 - 4	Same as above	Same as above
Acoustic Side-Scan Sonar	Tow depths 30-10,000 m; depth sensing 100-11,000 m	0 - 12	Swath width of 0.1-60 km	10's to 100's of meters above seabed
RoxAnn	Not applicable	Not applicable	Not applicable	Not applicable
Hyperspectral Imaging (HSI)	Centimeters to meters, possibly 10's to 100's of meters	Aircraft speed can be varied - as low as 90 knots	Swath width 100's to 1,000's of meters	Kilometers above sea surface
LIDAR (4 types)	50 m	Aircraft speed can be varied depending on rate of coverage desired	Several meters	Same as above

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The objective of this report is to identify and describe emerging technologies that may represent improved tools for conducting environmental assessments of aquatic habitats. For many Corps projects, required assessments are difficult to obtain due to logistical constraints, cost factors, and other limitations inherent to sampling submerged habitats and their biological resources. Recent advances in acoustic and optical sensor technologies offer promise to yield meaningful data at various spatial scales and levels of resolution.

Eleven sensor systems were examined and evaluated in terms of equipment specifications, logistical support requirements, type and utility of data products, spatial coverage and information return rates, and other factors. Sensor systems were categorized based on platform type: on-bottom sensors, in-water sensors, or airborne sensors. On-bottom sensors include sediment profile imaging, hyperspectral UV imaging spectrometry, megahertz acoustic sled, and acoustic subseabed interrogator

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systems. In-water sensors include laser line scan, gamma isotope mapping, continuous sediment sampling, acoustic side-scan sonar, and ROXANN systems. Airborne sensors include hyperspectral airborne imaging and light detection and ranging systems.

No single sensor has sufficient dynamic range to satisfy all conceivable requirements for surveys of soft- and hard-bottom habitats and associated fishery resources. However, at appropriate temporal and spatial scales, singly or in combination, these sensor systems afford powerful capabilities to perform environmental assessments.

Most sensors described in this report are still in developmental stages and therefore entail significant capital costs as well as expertise to implement and process derived data. In the short term, these cost-related limitations will have to be balanced against value of environmental information obtained. However, in the long term, as mobilization/demobilization costs are reduced, each system represents a significant advance in available technology for aquatic habitat assessment.